Probing particle physics with neutrino telescopes

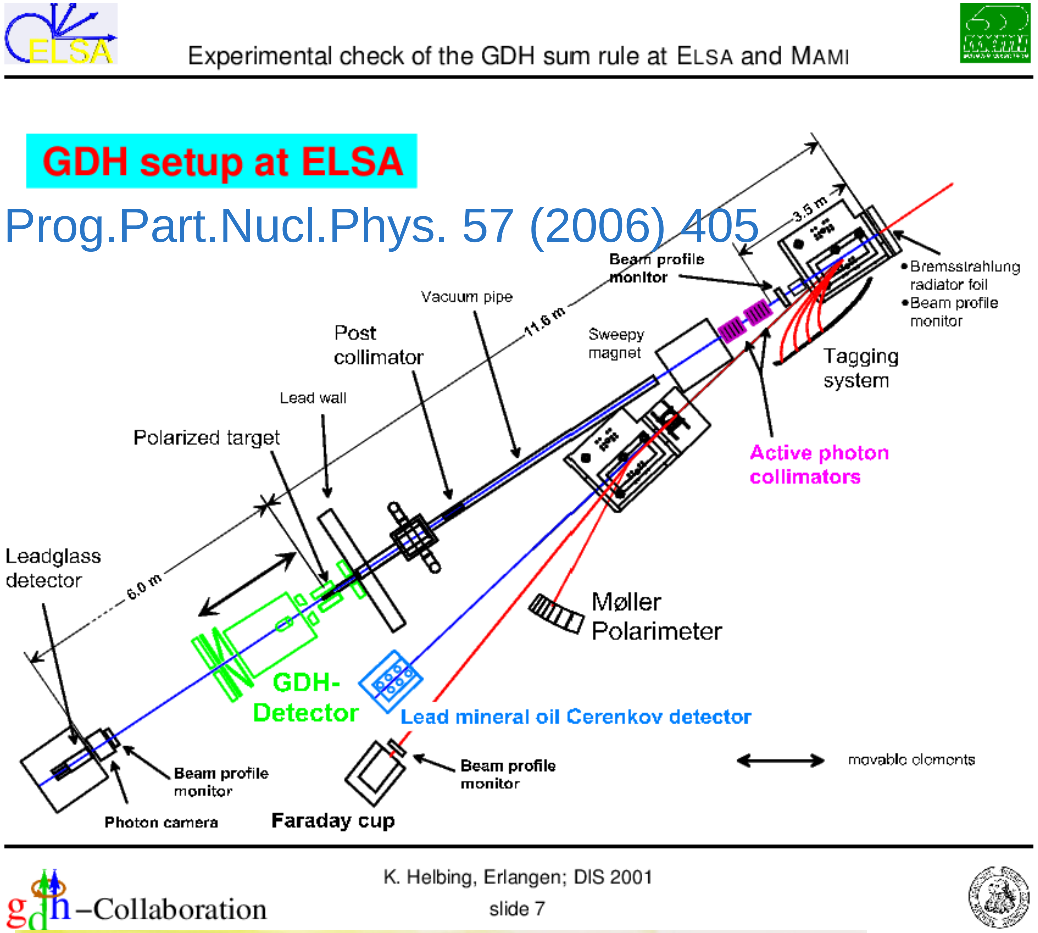
Klaus Helbing

Largely based on Eur.Phys.J. C78 (2018), 924

BERGISCHE
UNIVERSITÄT
WUPPERTAL

Kitzbühel, AvH-Kolleg 06/2019

Humboldt tribute



Experimental check of the GDH sum rule at ELSA and MAMI

GDH setup at ELSA

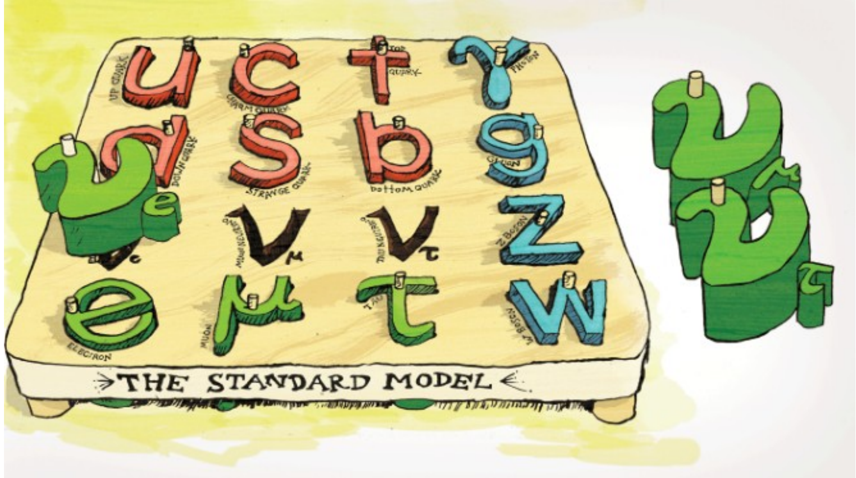
Prog.Part.Nucl.Phys. 57 (2006) 405

K. Helbing, Erlangen; DIS 2001

slide 7

gdh–Collaboration

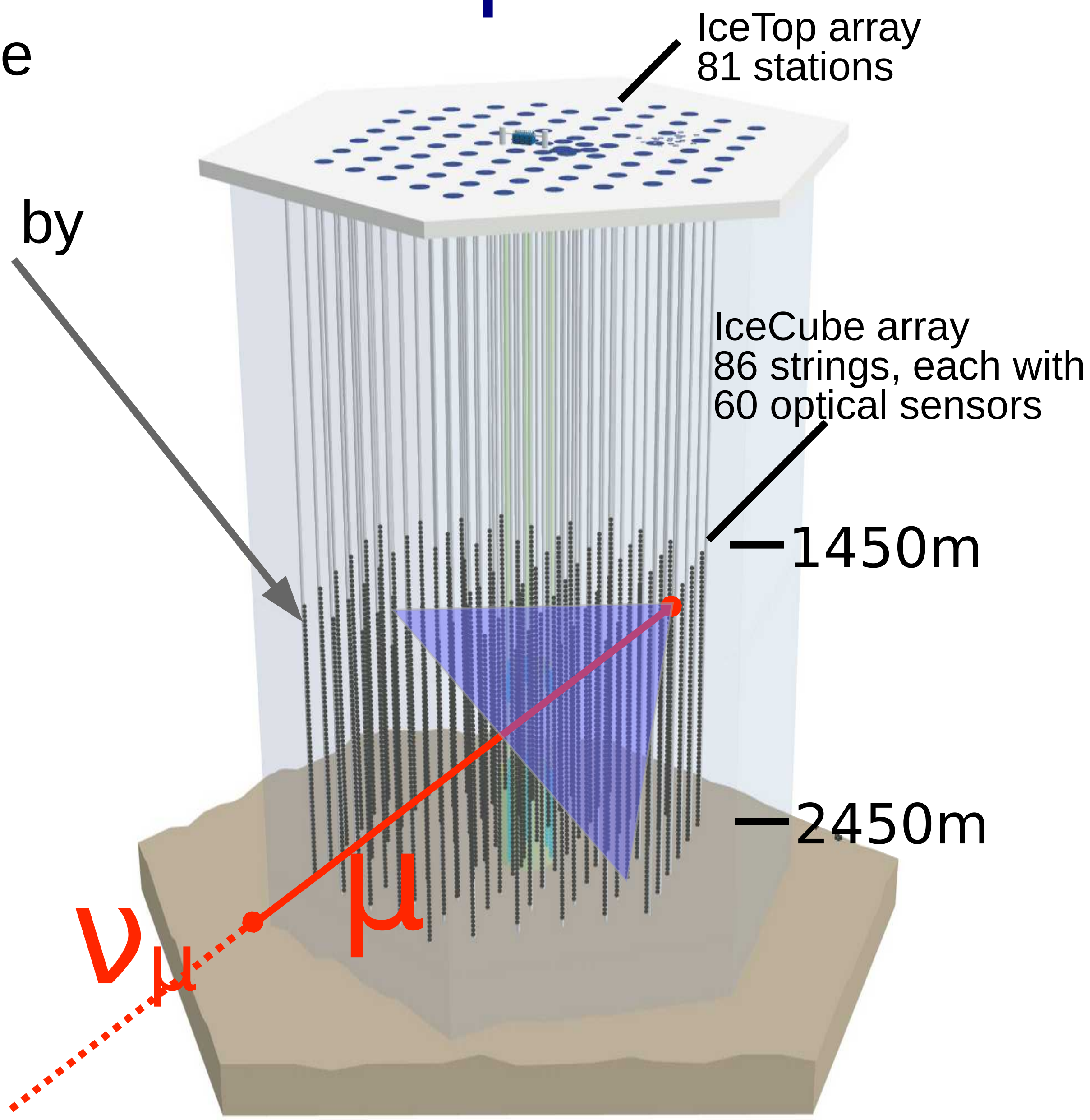
- Hadron physics → ~ 2002
- GDH sum rule (Bass talk)
- Primary interest:
  LIV etc … remained
- Lynen fellow →
  astroparticle physics
- IceCube @ Berkeley
- Later ν mass: KATRIN



$$H \Rightarrow m_\nu$$

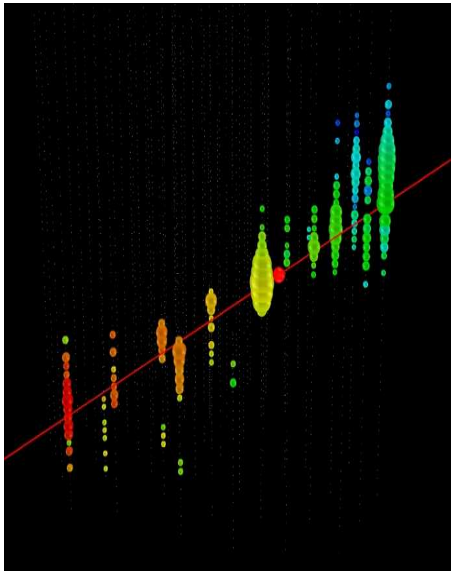
Primary working principle of Neutrino Telescopes

- Particles interact with the deep clear ice
- Emitted light is detected by sensors
  - Cherenkov Light
  - Bremsstrahlung
  - Pair production
  - Photonuclear interactions
  - Luminescence



Neutrino Event Signatures

CC Muon Neutrino

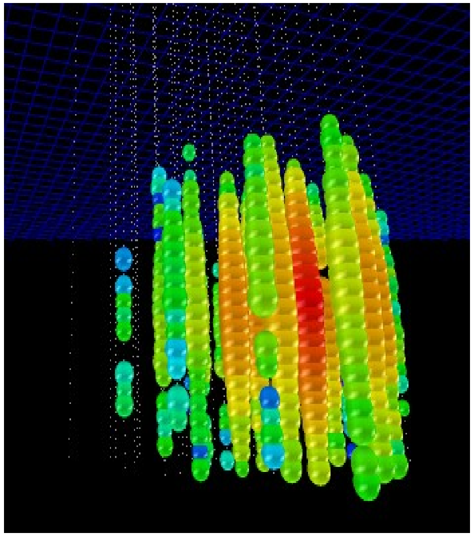


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current Electron Neutrino

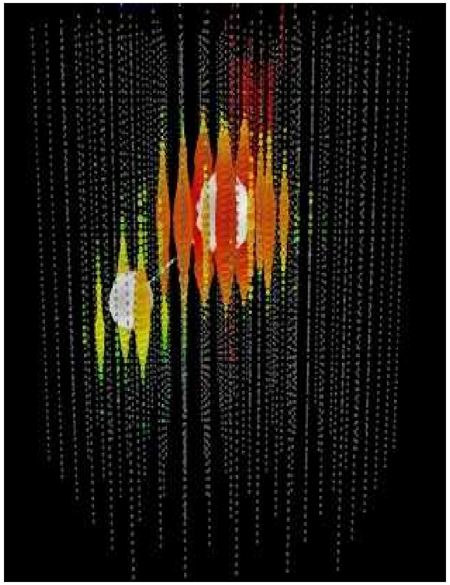


$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)
≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)

CC Tau Neutrino

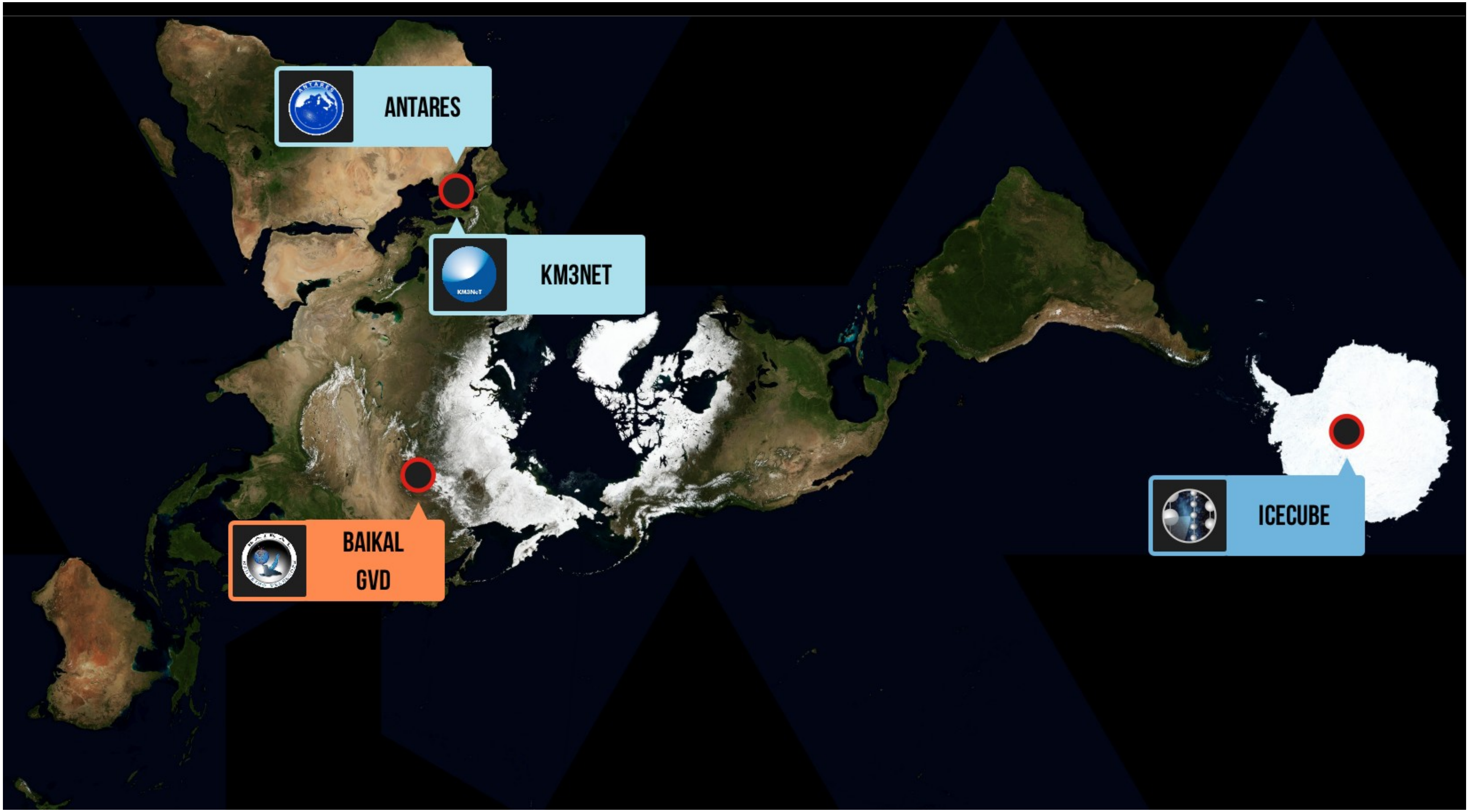


$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures (simulation)

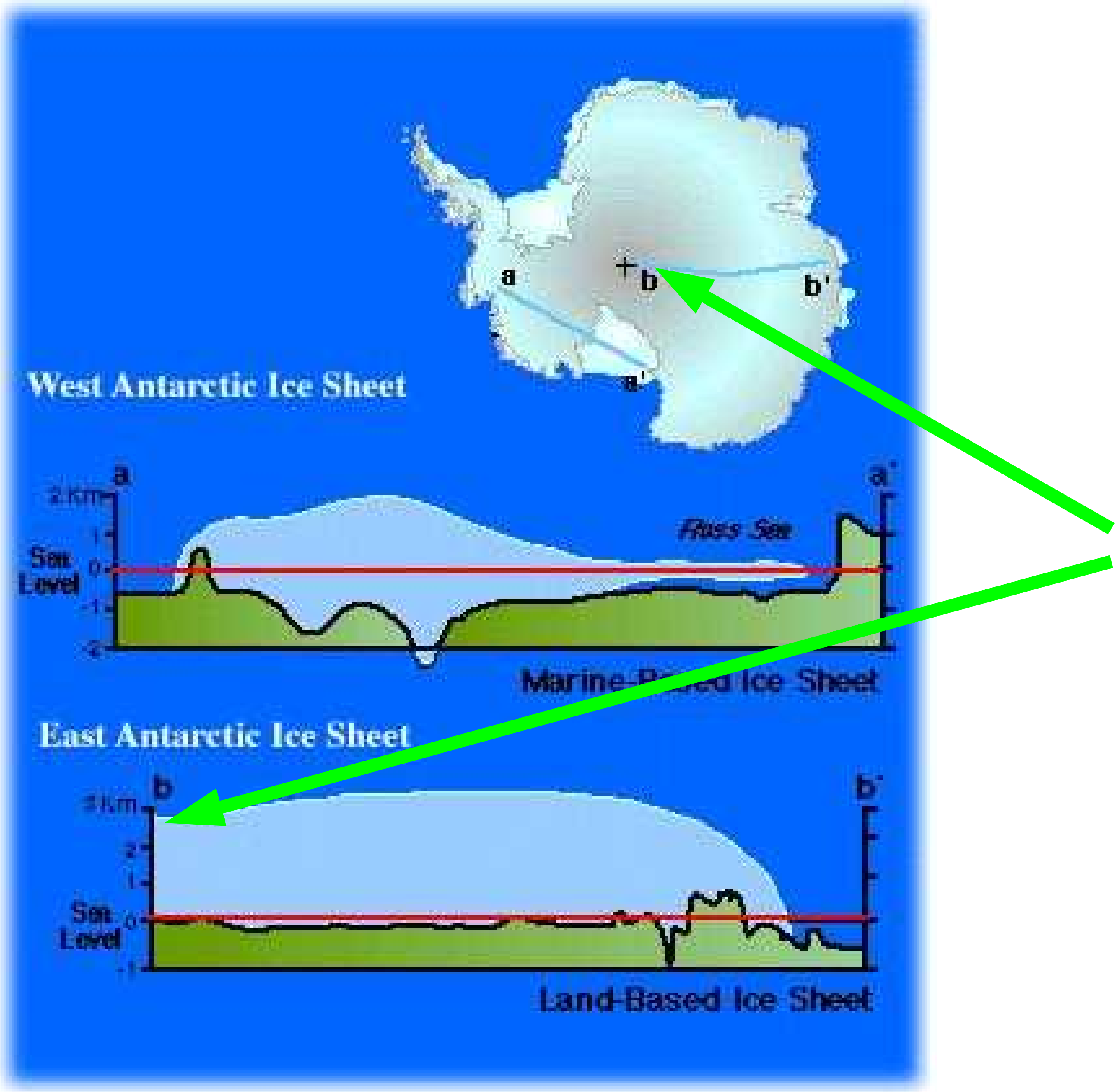
& BSM signatures … more in a bit !

Neutrino Telescope Sites



Deep natural sites with water or ice

South Pole ice

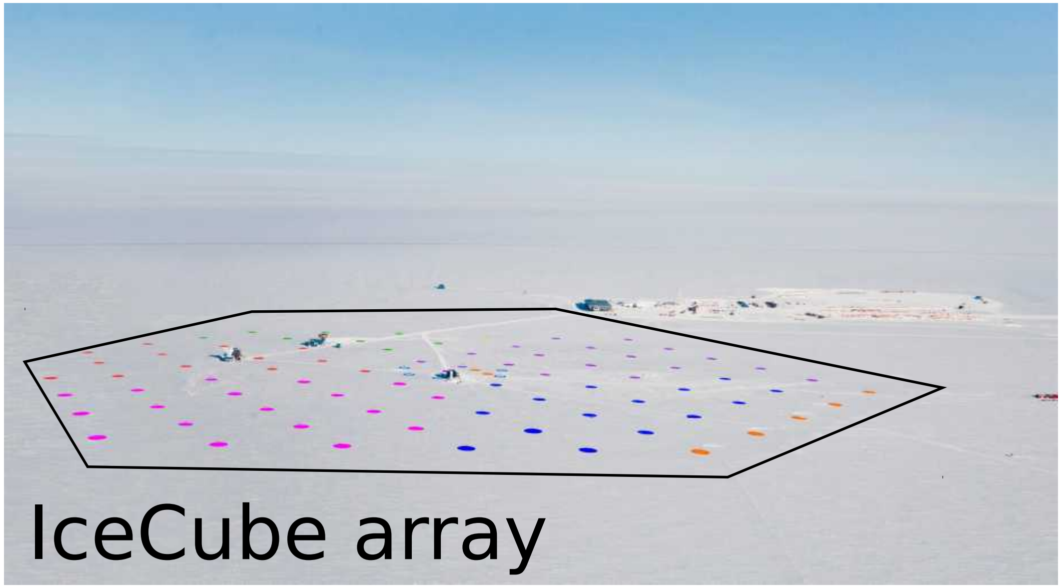


South Pole

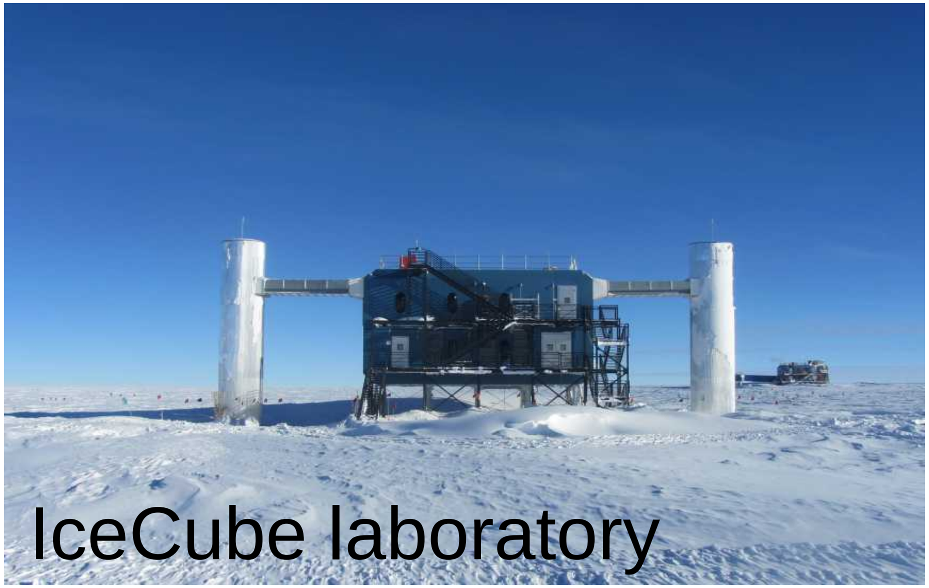
IceCube Neutrino Observatory

Amundson-Scott Station

The South Pole



IceCube array



IceCube laboratory

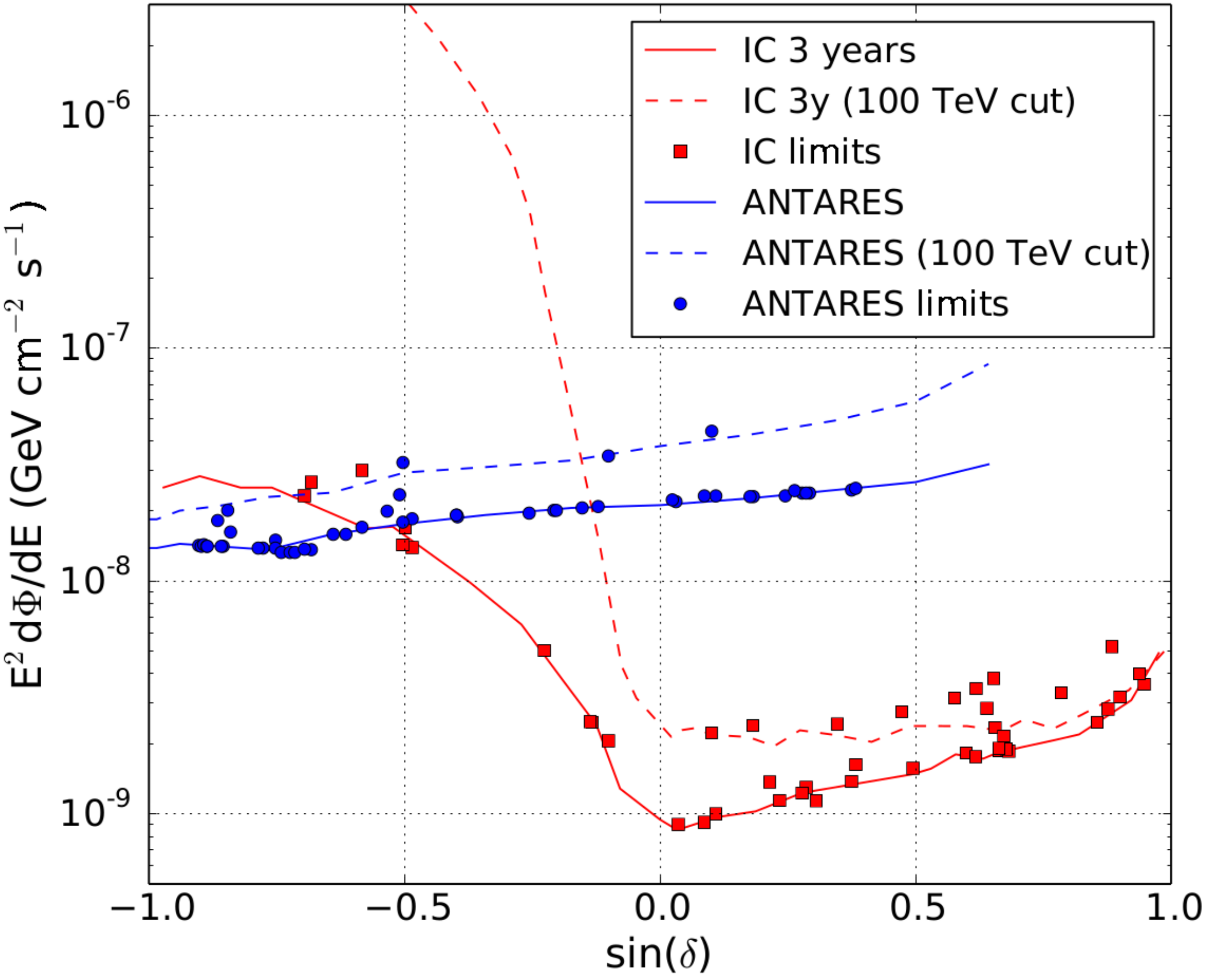
Complementary deployment environments

- Accessible year round
- Reachable within few hours of travel

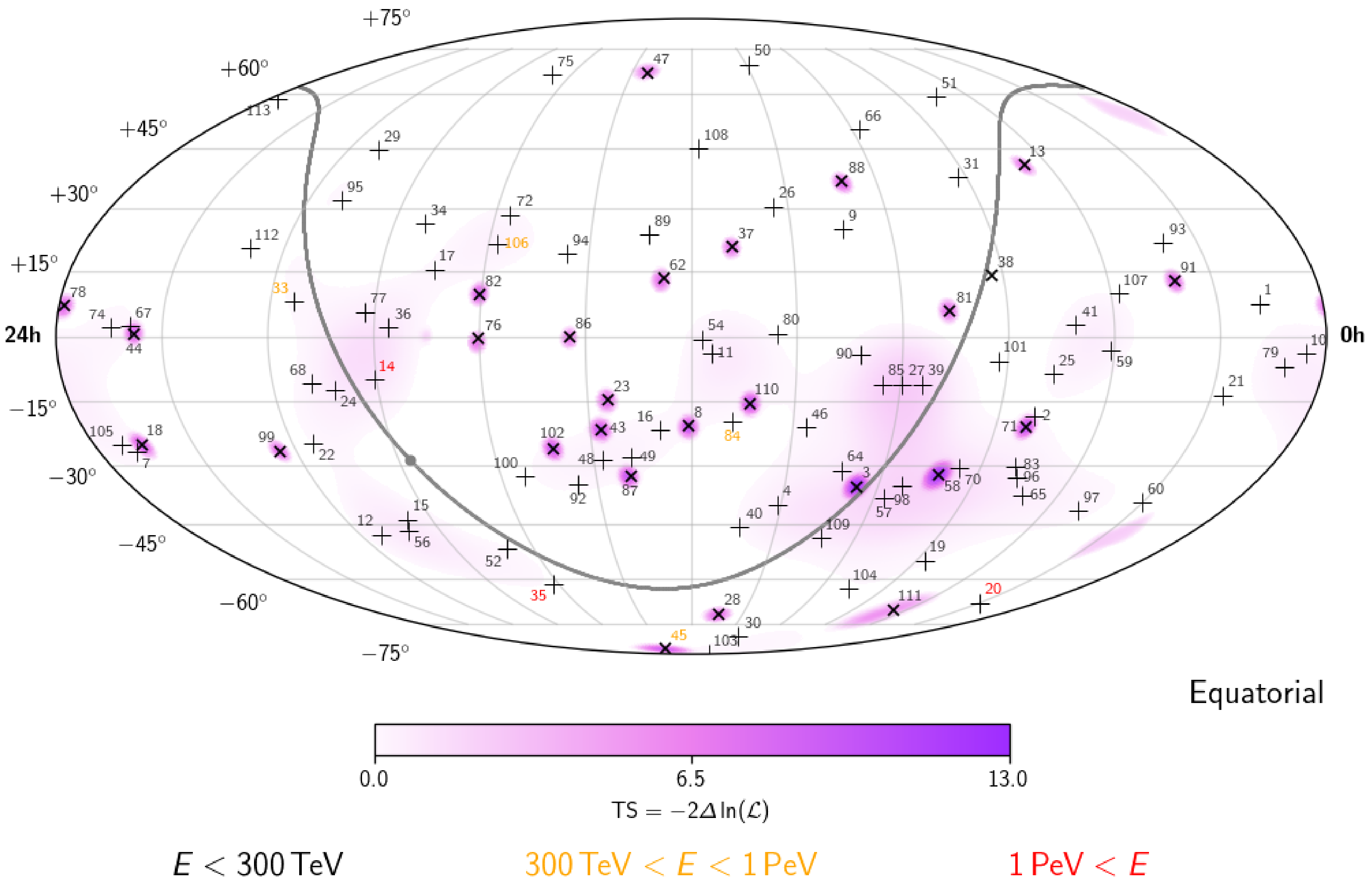
- No sea sickness
- Work flow crucial

Sensitivities of Antares and IceCube for the whole sky

Astrophys.J. 823 (2016), 65



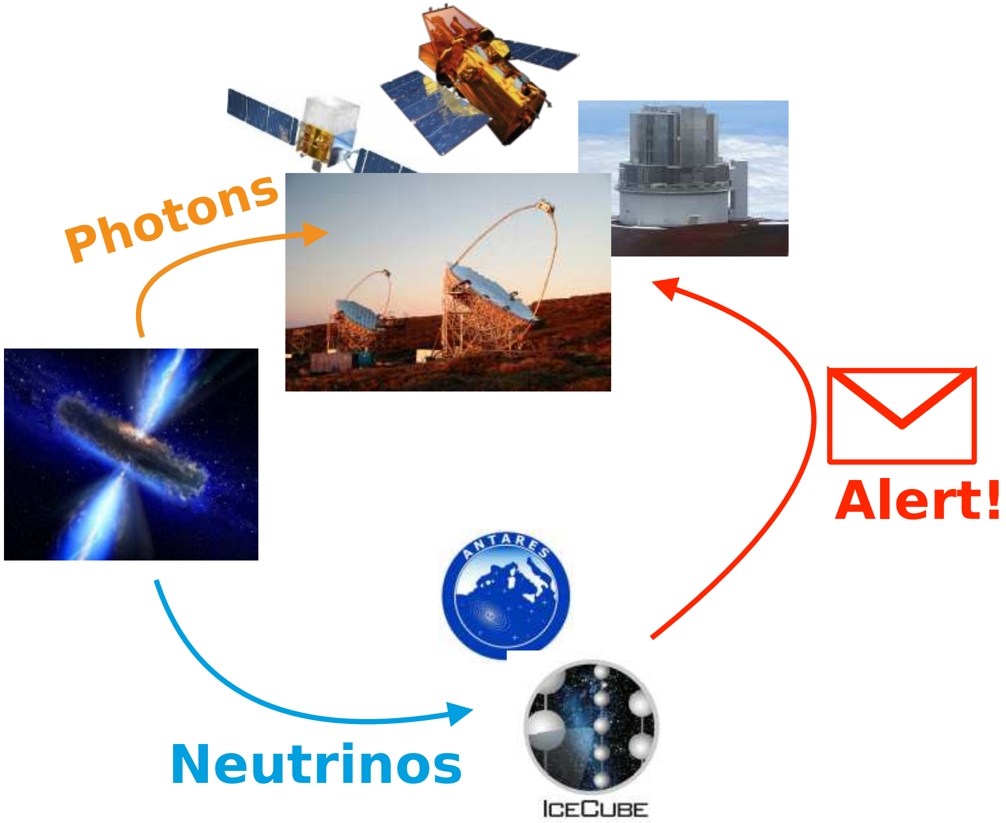
Astrophysical Neutrinos: >100 … and counting



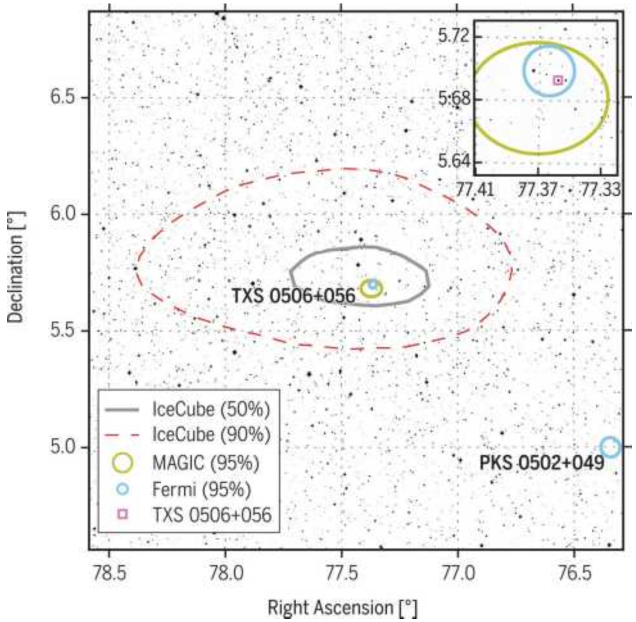
but **isotropic** so far!

First evidence for a neutrino source!

Real-time alerts

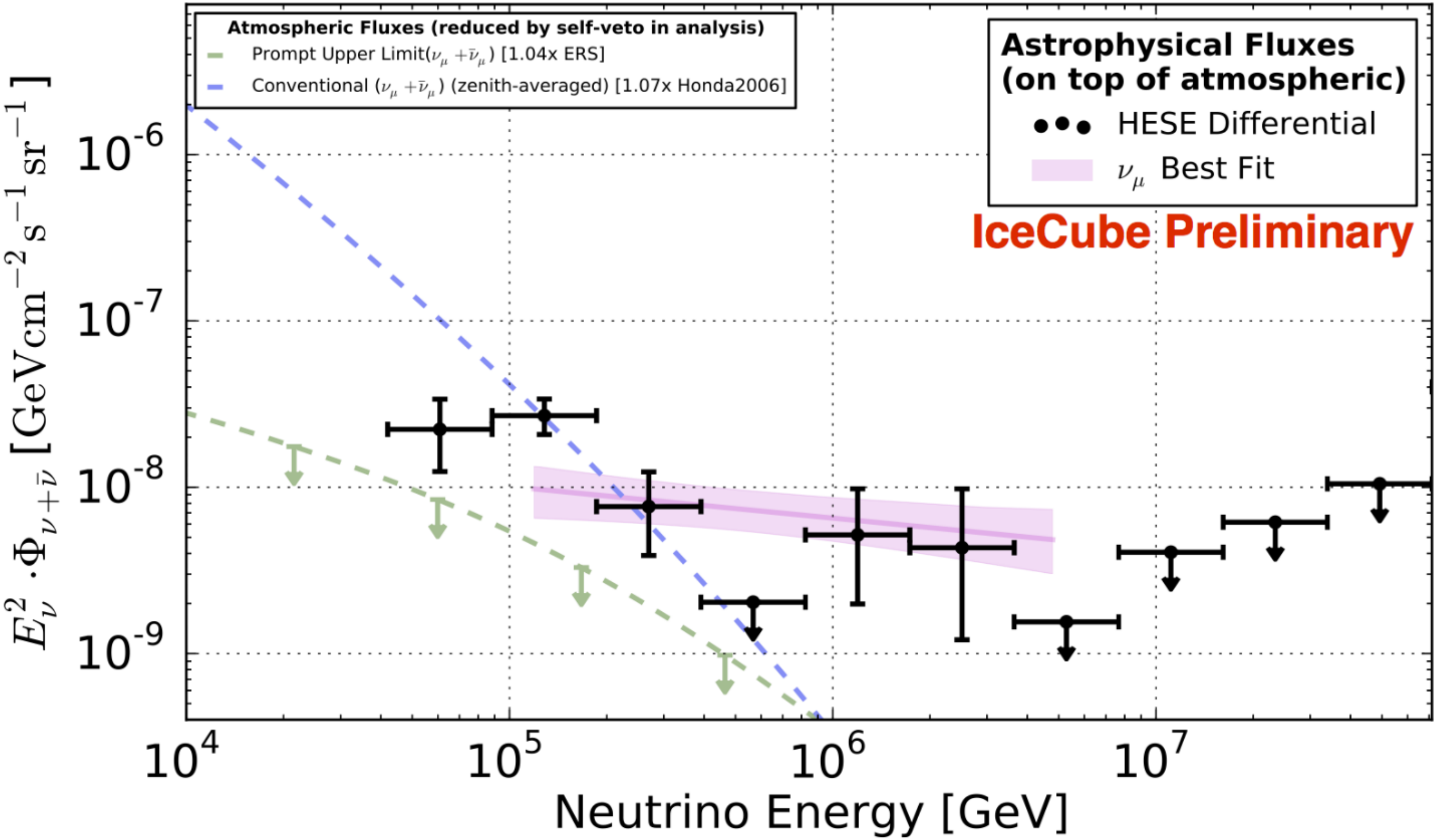


Science 361 (2018) no.6398, eaat1378



3σ correlation of IC-170922A (~300 TeV) with the flaring blazar TXS 0506+056

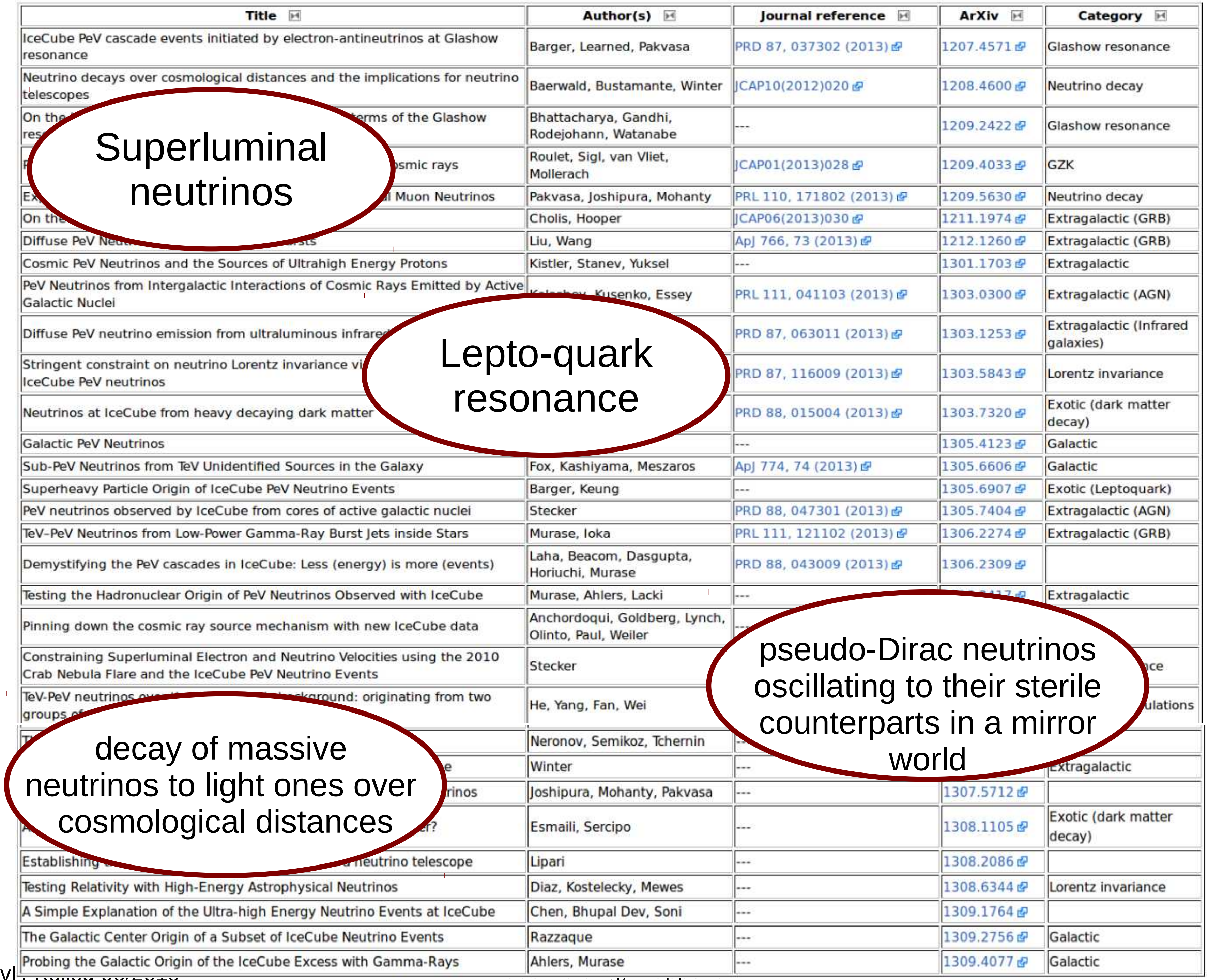
Neutrino energy spectrum



Phys.Rev.Lett. 113 (2014) 101101

Astrophys. J.833 (2016) 3

Interpretation of energy distribution by the community



Title	Author(s)	Journal reference	ArXiv	Category
IceCube PeV cascade events initiated by electron-antineutrinos at Glashow resonance	Barger, Learned, Pakvasa	PRD 87, 037302 (2013)	1207.4571	Glashow resonance
Neutrino decays over cosmological distances and the implications for neutrino telescopes	Baerwald, Bustamante, Winter	JCAP10(2012)020	1208.4600	Neutrino decay
On the [illegible] terms of the Glashow res[illegible]	Bhattacharya, Gandhi, Rodejohann, Watanabe	---	1209.2422	Glashow resonance
F[illegible] osmic rays	Roulet, Sigl, van Vliet, Mollerach	JCAP01(2013)028	1209.4033	GZK
Ex[illegible] l Muon Neutrinos	Pakvasa, Joshipura, Mohanty	PRL 110, 171802 (2013)	1209.5630	Neutrino decay
On the [illegible]	Cholis, Hooper	JCAP06(2013)030	1211.1974	Extragalactic (GRB)
Diffuse PeV Neu[illegible] rsts	Liu, Wang	ApJ 766, 73 (2013)	1212.1260	Extragalactic (GRB)
Cosmic PeV Neutrinos and the Sources of Ultrahigh Energy Protons	Kistler, Stanev, Yuksel	---	1301.1703	Extragalactic
PeV Neutrinos from Intergalactic Interactions of Cosmic Rays Emitted by Active Galactic Nuclei	[illegible], Kusenko, Essey	PRL 111, 041103 (2013)	1303.0300	Extragalactic (AGN)
Diffuse PeV neutrino emission from ultraluminous infrare[illegible]	[illegible]	PRD 87, 063011 (2013)	1303.1253	Extragalactic (Infrared galaxies)
Stringent constraint on neutrino Lorentz invariance vi[illegible] IceCube PeV neutrinos	[illegible]	PRD 87, 116009 (2013)	1303.5843	Lorentz invariance
Neutrinos at IceCube from heavy decaying dark matter	[illegible]	PRD 88, 015004 (2013)	1303.7320	Exotic (dark matter decay)
Galactic PeV Neutrinos	[illegible]	---	1305.4123	Galactic
Sub-PeV Neutrinos from TeV Unidentified Sources in the Galaxy	Fox, Kashiyama, Meszaros	ApJ 774, 74 (2013)	1305.6606	Galactic
Superheavy Particle Origin of IceCube PeV Neutrino Events	Barger, Keung	---	1305.6907	Exotic (Leptoquark)
PeV neutrinos observed by IceCube from cores of active galactic nuclei	Stecker	PRD 88, 047301 (2013)	1305.7404	Extragalactic (AGN)
TeV–PeV Neutrinos from Low-Power Gamma-Ray Burst Jets inside Stars	Murase, Ioka	PRL 111, 121102 (2013)	1306.2274	Extragalactic (GRB)
Demystifying the PeV cascades in IceCube: Less (energy) is more (events)	Laha, Beacom, Dasgupta, Horiuchi, Murase	PRD 88, 043009 (2013)	1306.2309	
Testing the Hadronuclear Origin of PeV Neutrinos Observed with IceCube	Murase, Ahlers, Lacki	---	[illegible]	Extragalactic
Pinning down the cosmic ray source mechanism with new IceCube data	Anchordoqui, Goldberg, Lynch, Olinto, Paul, Weiler	[illegible]	[illegible]	[illegible]
Constraining Superluminal Electron and Neutrino Velocities using the 2010 Crab Nebula Flare and the IceCube PeV Neutrino Events	Stecker	[illegible]	[illegible]	[illegible]nce
TeV-PeV neutrinos ov[illegible]kground: originating from two groups of[illegible]	He, Yang, Fan, Wei	[illegible]	[illegible]	[illegible]ulations
T[illegible]	Neronov, Semikoz, Tchernin	---	[illegible]	[illegible]
[illegible]e	Winter	---	[illegible]	Extragalactic
[illegible]rinos	Joshipura, Mohanty, Pakvasa	---	1307.5712	
A[illegible]r?	Esmaili, Serpico	---	1308.1105	Exotic (dark matter decay)
Establishing [illegible] neutrino telescope	Lipari	---	1308.2086	
Testing Relativity with High-Energy Astrophysical Neutrinos	Diaz, Kostelecky, Mewes	---	1308.6344	Lorentz invariance
A Simple Explanation of the Ultra-high Energy Neutrino Events at IceCube	Chen, Bhupal Dev, Soni	---	1309.1764	
The Galactic Center Origin of a Subset of IceCube Neutrino Events	Razzaque	---	1309.2756	Galactic
Probing the Galactic Origin of the IceCube Excess with Gamma-Rays	Ahlers, Murase	---	1309.4077	Galactic

Superluminal neutrinos

Lepto-quark resonance

pseudo-Dirac neutrinos oscillating to their sterile counterparts in a mirror world

decay of massive neutrinos to light ones over cosmological distances

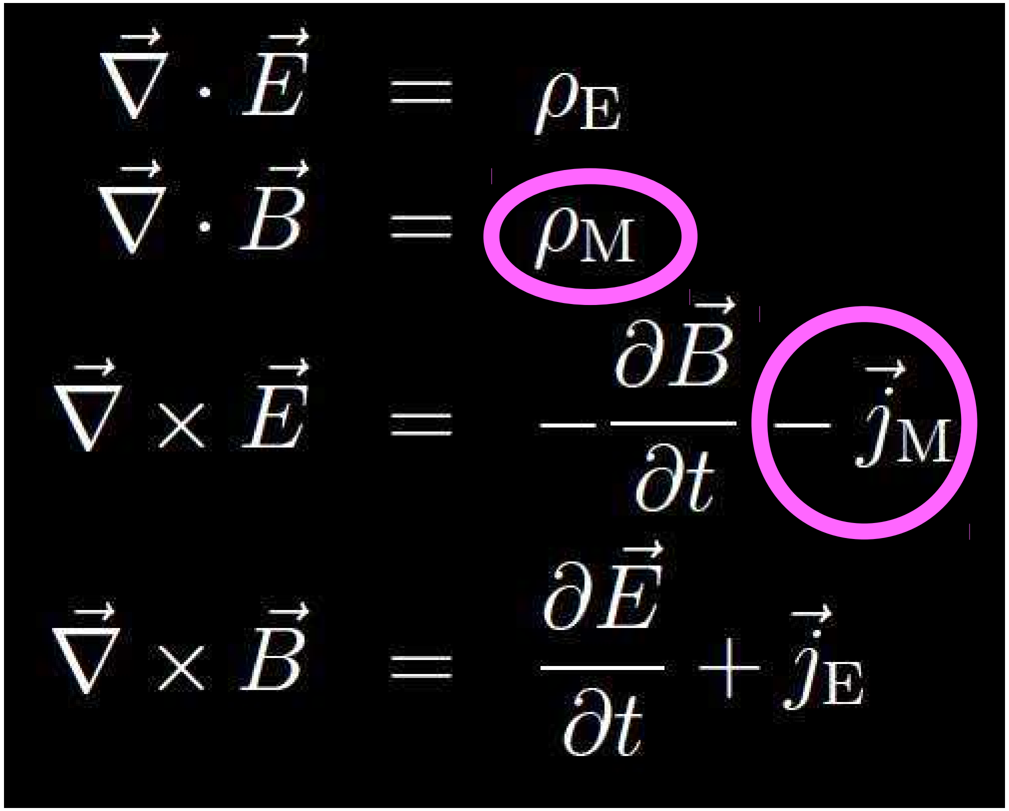
This is not what the rest of this talk is about

… but non the less exotic …

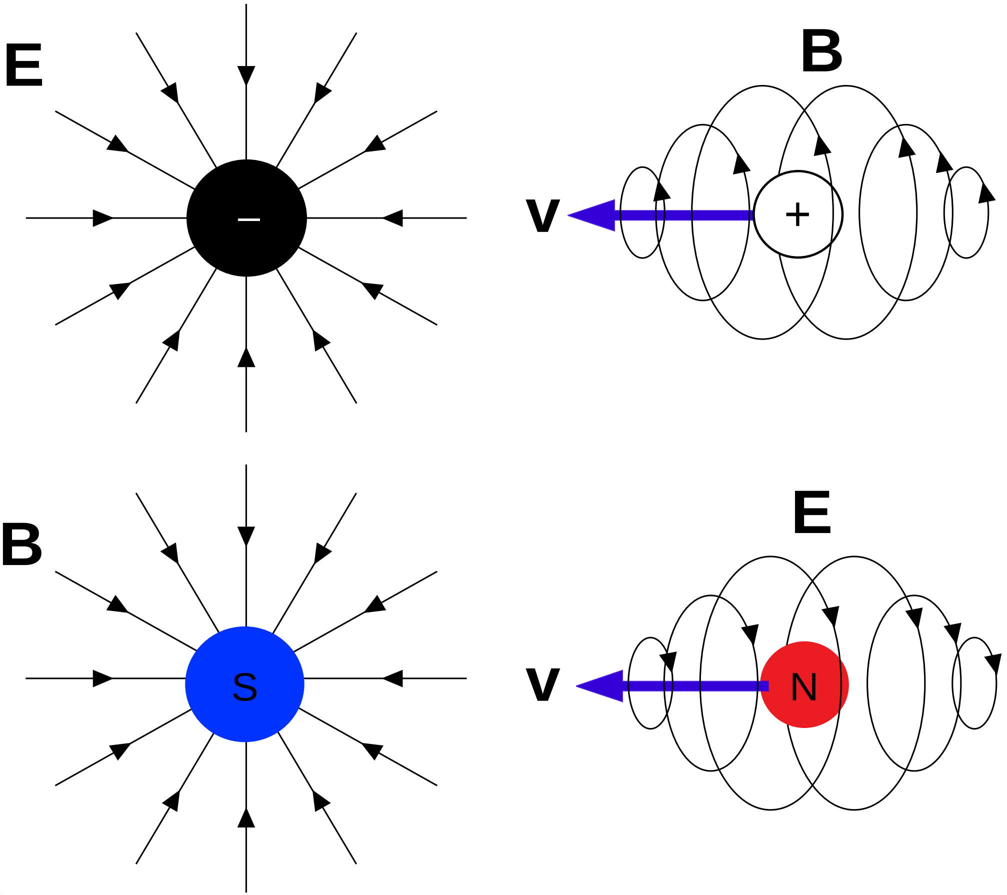
- Direct signatures of BSM physics
  - **Magnetic monopoles**
  - SUSY pair-production
  - HNLs & fractional charges
- Indirect signatures:
  - WIMPs: annihilation and decay
  - (Micro-) black hole creation and evaporation

… sorry, need to skip over oscillations and Axions

Symmetric Maxwell equations – classical field theory



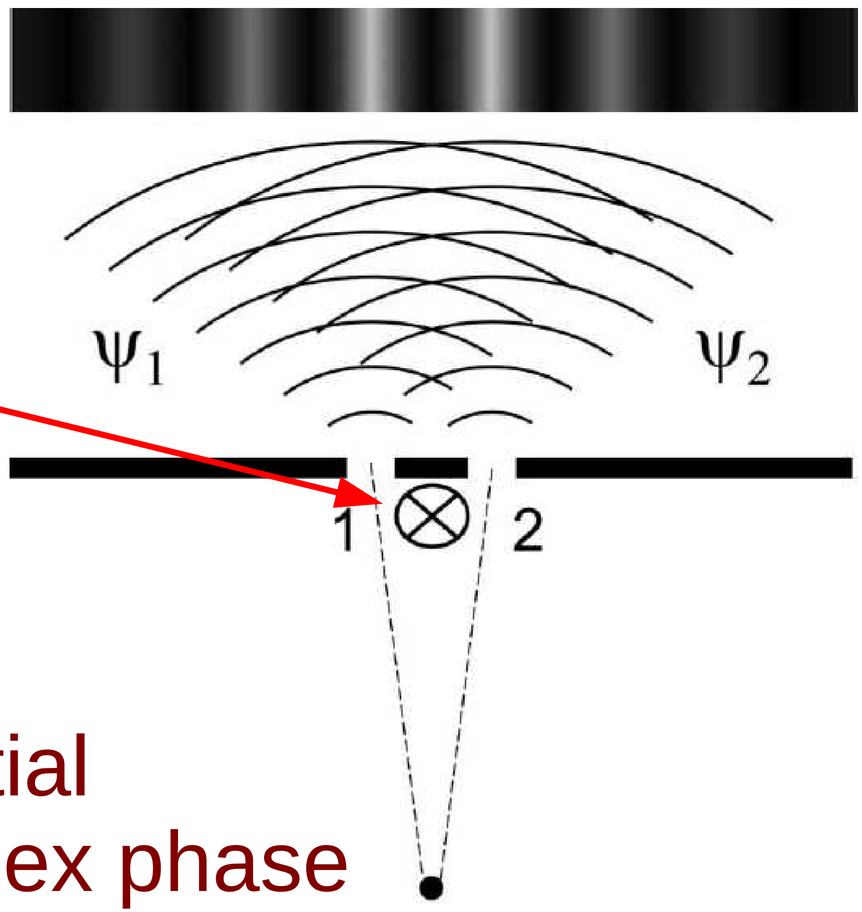
$$
\begin{aligned}
\vec{\nabla}\cdot\vec{E} &= \rho_{\mathrm{E}}\\
\vec{\nabla}\cdot\vec{B} &= \boxed{\rho_{\mathrm{M}}}\\
\vec{\nabla}\times\vec{E} &= -\frac{\partial\vec{B}}{\partial t}\boxed{-\vec{j}_{\mathrm{M}}}\\
\vec{\nabla}\times\vec{B} &= \frac{\partial\vec{E}}{\partial t}+\vec{j}_{\mathrm{E}}
\end{aligned}
$$



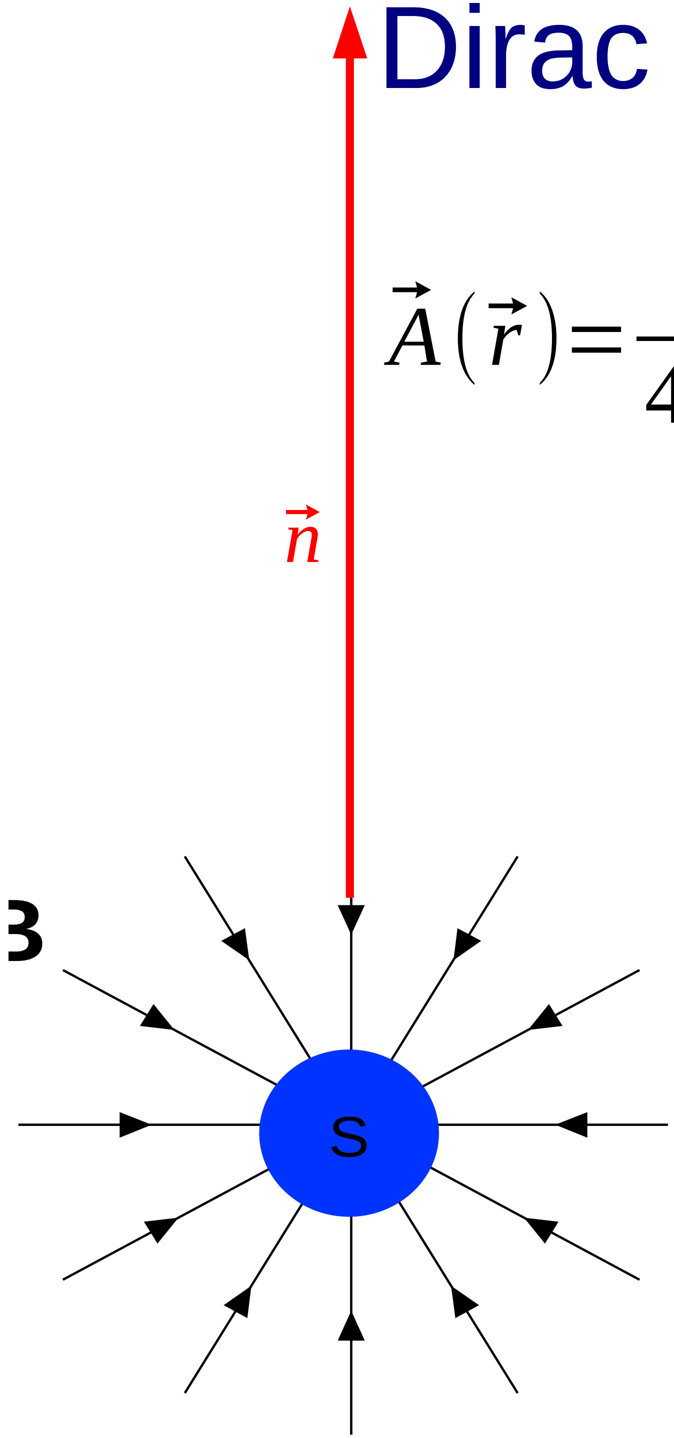
vector potential $\vec{A}\ :\ \vec{\nabla}\times\vec{A}=\vec{B}$

Dirac Monopole

$$\vec{A}(\vec{r}) = \frac{g}{4\pi r}\,\frac{\vec{r}\times\vec{n}}{r-\vec{r}\cdot\vec{n}}$$

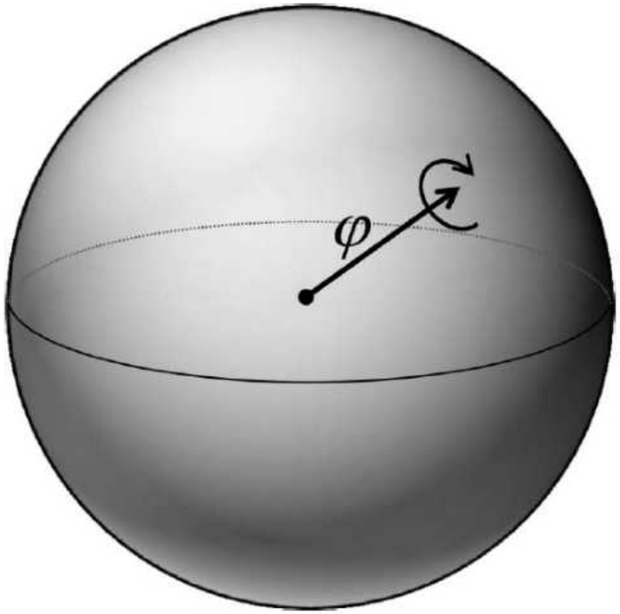


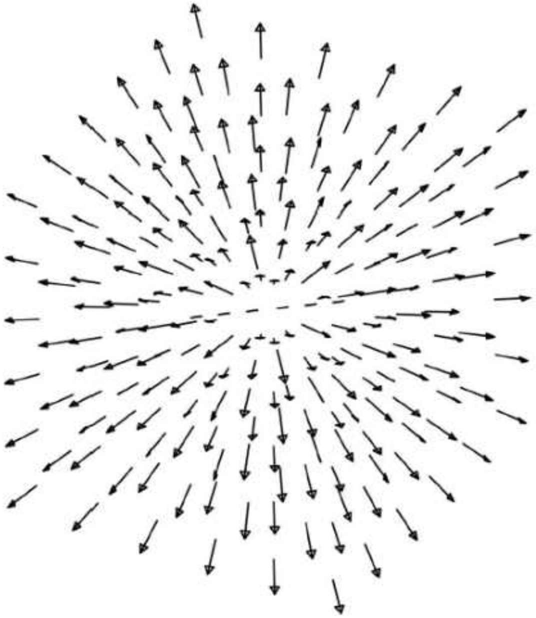
- Vector potential affects complex phase of wave function → interference
- Interference cancels if $g = g_0 = n \cdot 2\pi/e$
- Explains quantization of charge!



’t Hooft–Polyakov Monopoles

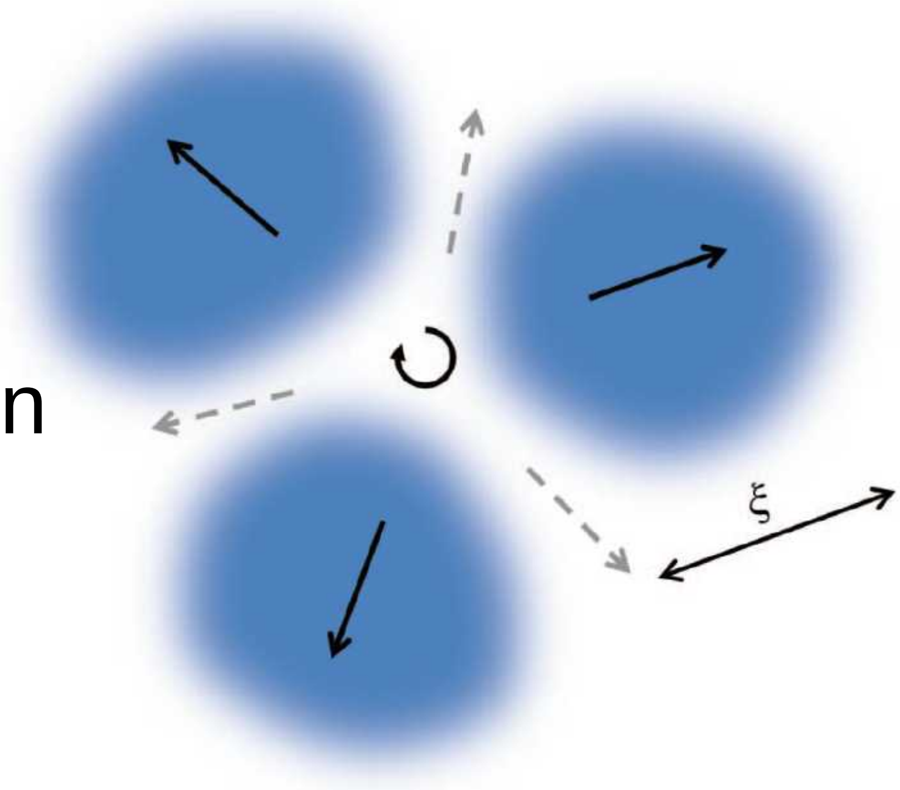
- Georgi–Glashow model: SU(5) for illustration
- Higgs field: φ^a, $a=1,2,3$
- Hedgehog configuration: Higgs field vector points away from origin everywhere
  → topologically stable
- Result: Magnetic Monopoles with $g = \mathbf{4}\pi/e$
  …twice the Dirac charge





Cosmic Monopoles

- Hot big bang:
  GUT symmetry breaks in a phase transition
- Higgs field chooses direction randomly but monotonous within interaction horizon.
- Kibble: Monopoles form at least one per horizon volume
  → “Monopole Problem”
- Inflationary phase of the Universe

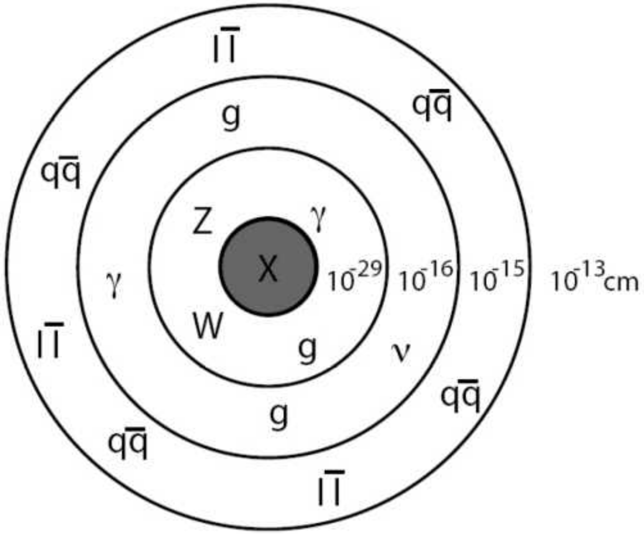


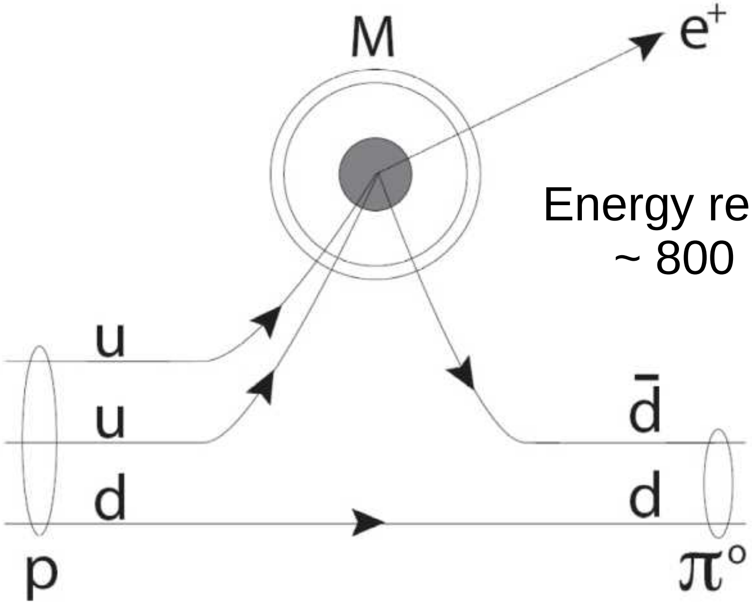
$$\rho_{mon}^{\#} \simeq 10^{-13}\,\mathrm{m}^{-3}$$

$$\rho_{mon} \simeq 10^{+4}\,\mathrm{GeV\,m}^{-3}$$

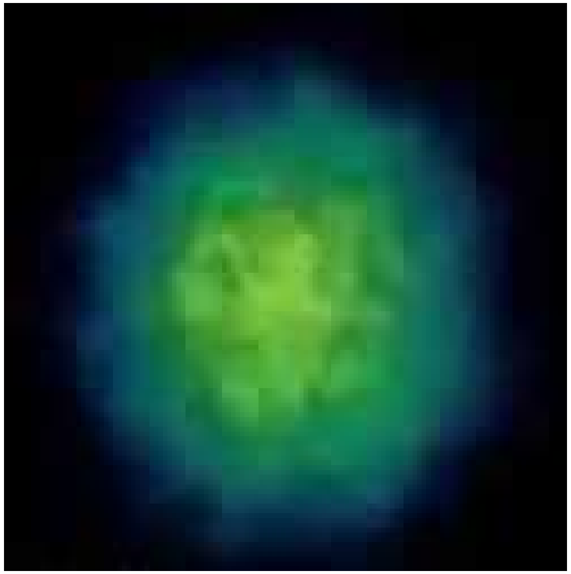
GUT Monopoles

- Generic predictions of GUTs
- Mass typically 10^{17} GeV
- May catalyze proton decay



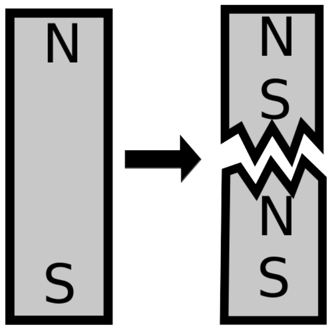


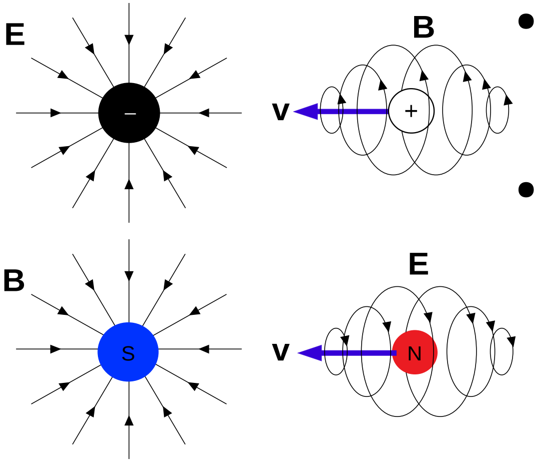
Energy released:
~ 800 MeV



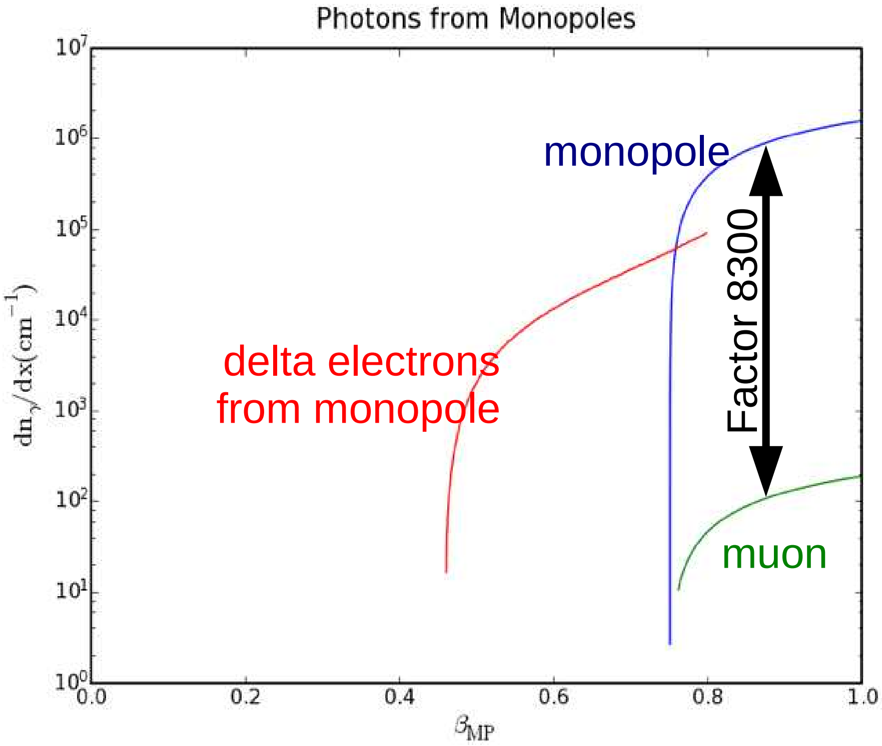
Lattice field theory simulation (A. Rajantie)
Contemp. Phys. 53 (2012) 195

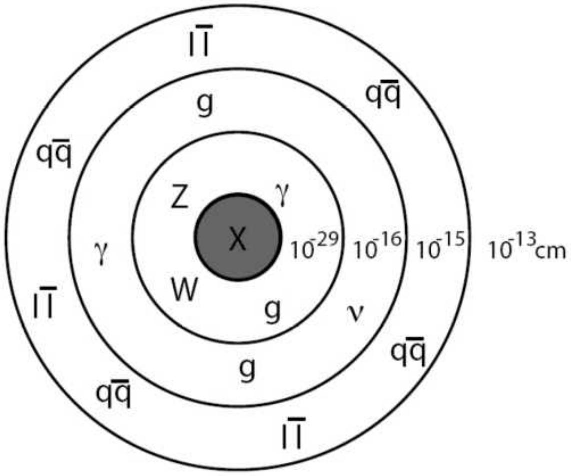
Detection of monopoles



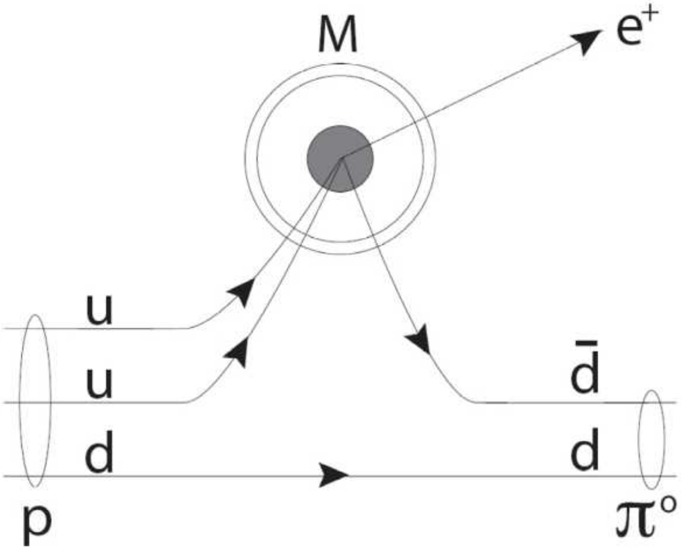


- Charge:
  $g \approx N \cdot 68.5\, e$
- Mass:
  $m = 10^4 - 10^{17}$ GeV
- Kinetic energy:
  $T = 10^9 - 10^{16}$ GeV
- **Cherenkov light:**
  $\boldsymbol{N_\gamma \propto (g \cdot n / e)^2}$
  $\boldsymbol{\propto 8300\, N_\gamma(\mu)}$



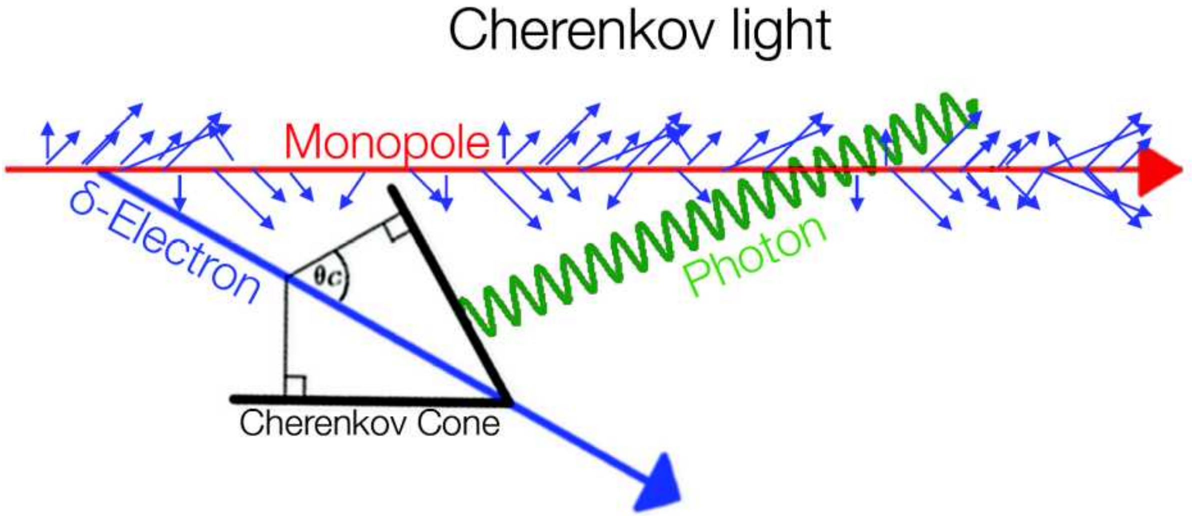


GUT monopole:
Onion like structure
containing the whole
world of GUT
→ nucleon decay catalysis



Monopole detection techniques

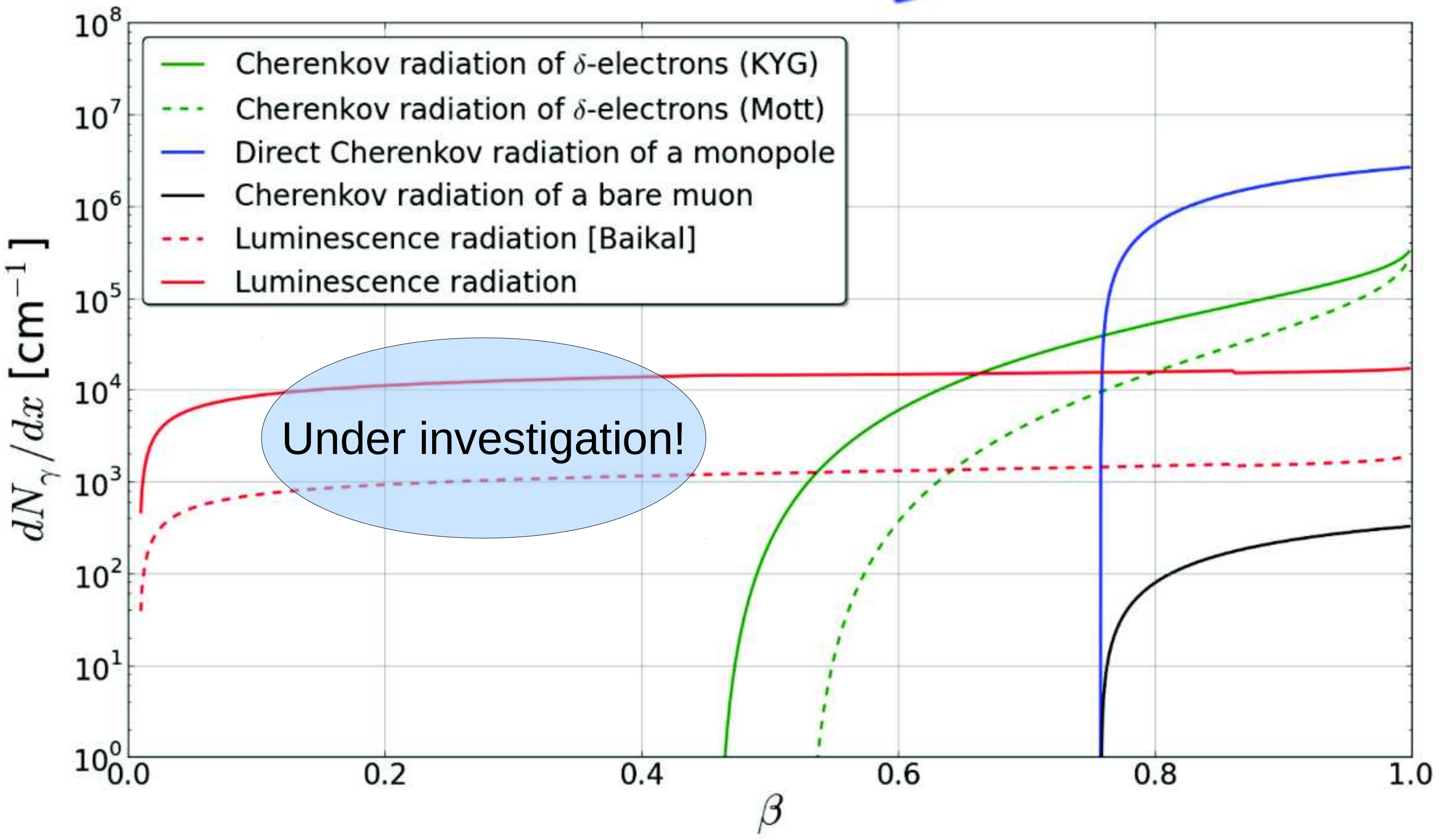
Monopoles with β > 0.5: indirect Cherenkov



Monopoles with β < 0.5:

– Nucleon decay catalysis

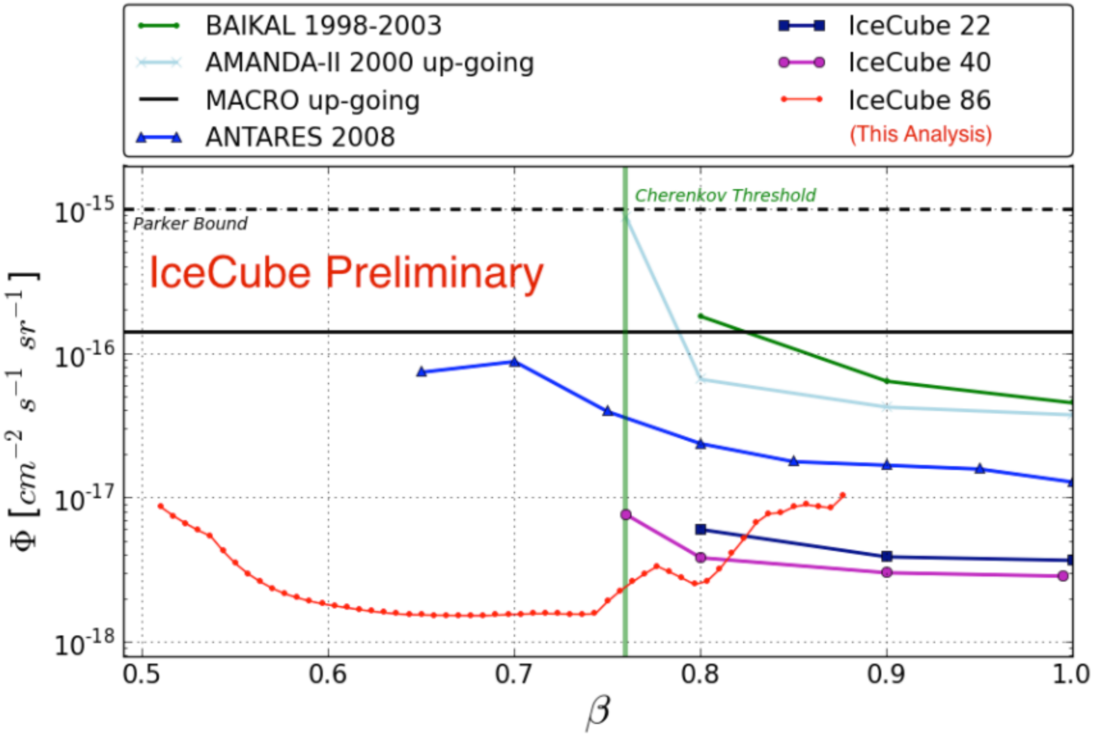
– Radio-luminescence



Under investigation!

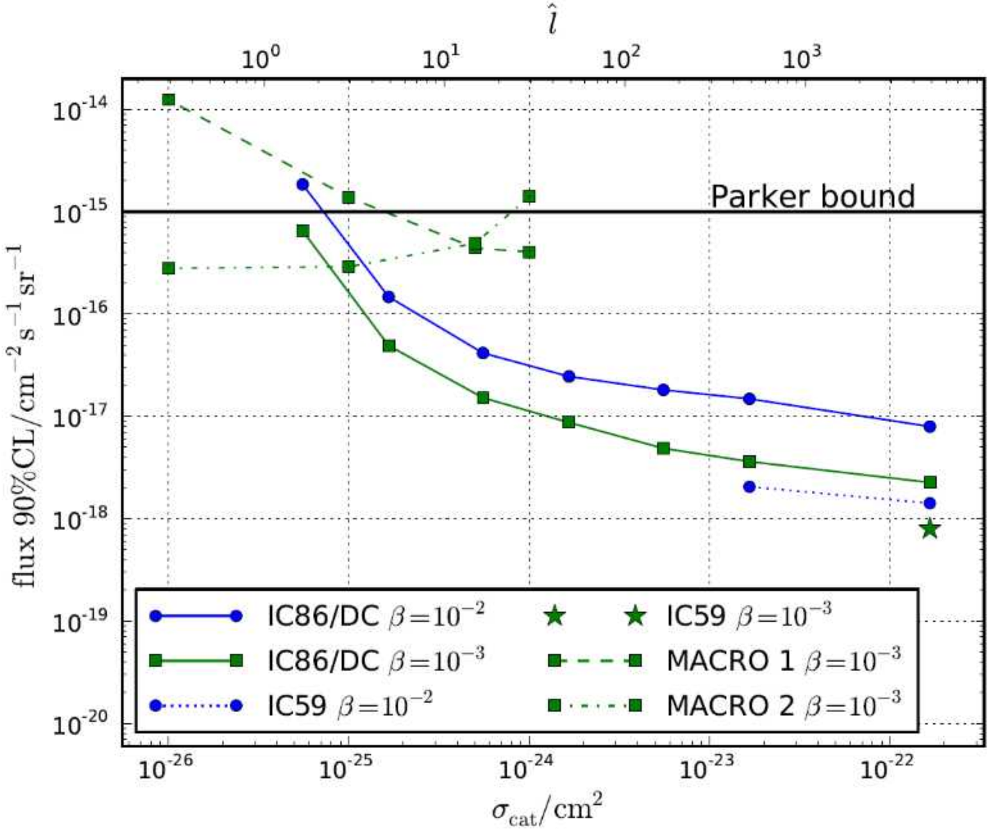
Monopole limits

Mildly and highly relativistic



Eur.Phys.J. C76 (2016) no.3, 133

Nucleon decay catalysis



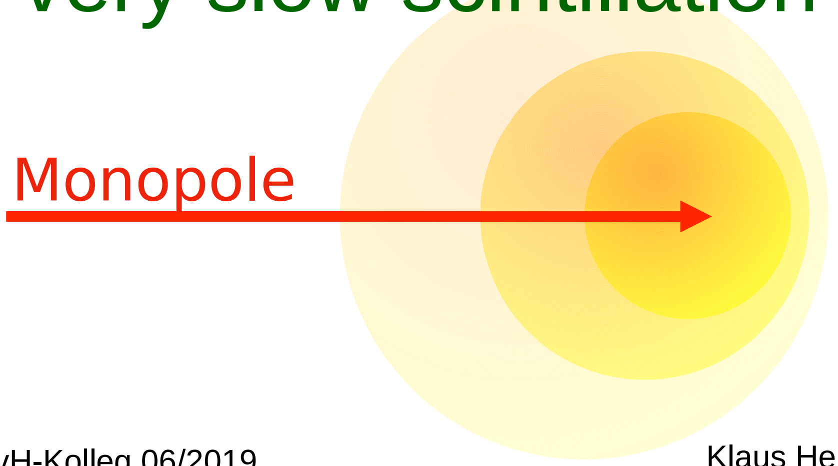
Eur.Phys.J. C74 (2014) no.7, 2938

Odd enough:
astrophysical neutrinos significant
background to relativistic monopoles!

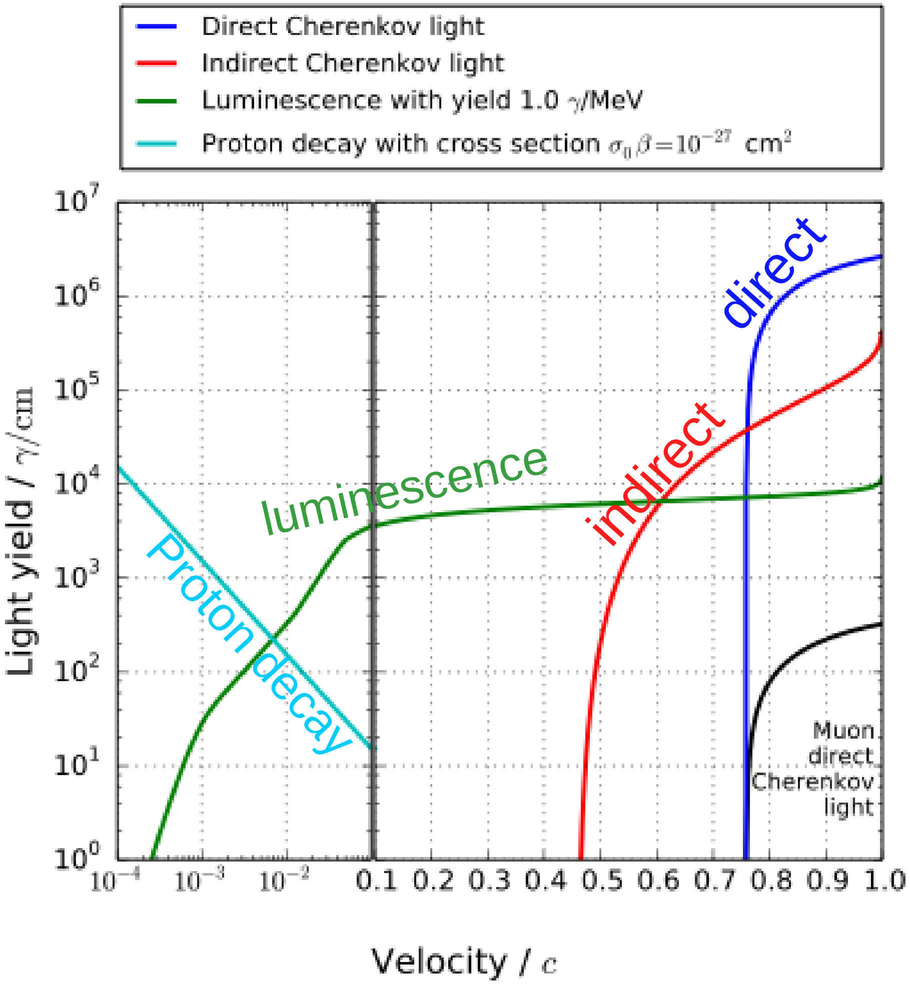
Radio-Luminescence

EPJ Web Conf. 164 (2017) 07019, arXiv:1610.06397

- highly ionizing, multiply charged particle
- exciting surrounding matter
- photon release at relaxation … basically very slow scintillation



Monopole light yield

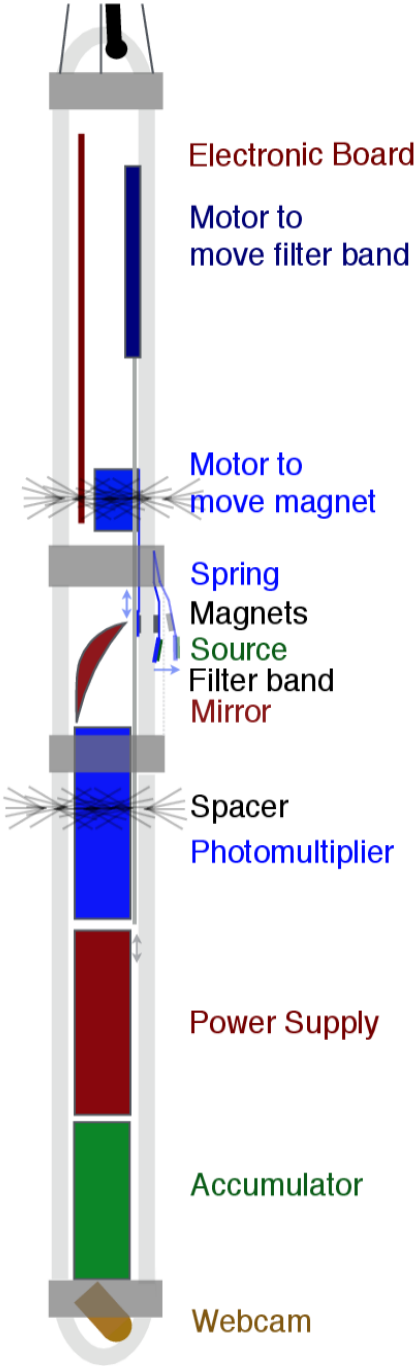


Luminescence Logging

supplement lab measurements with in-situ measurements

depth dependence of
- ice under pressure
- ice containing solubles / impurities
- temperature

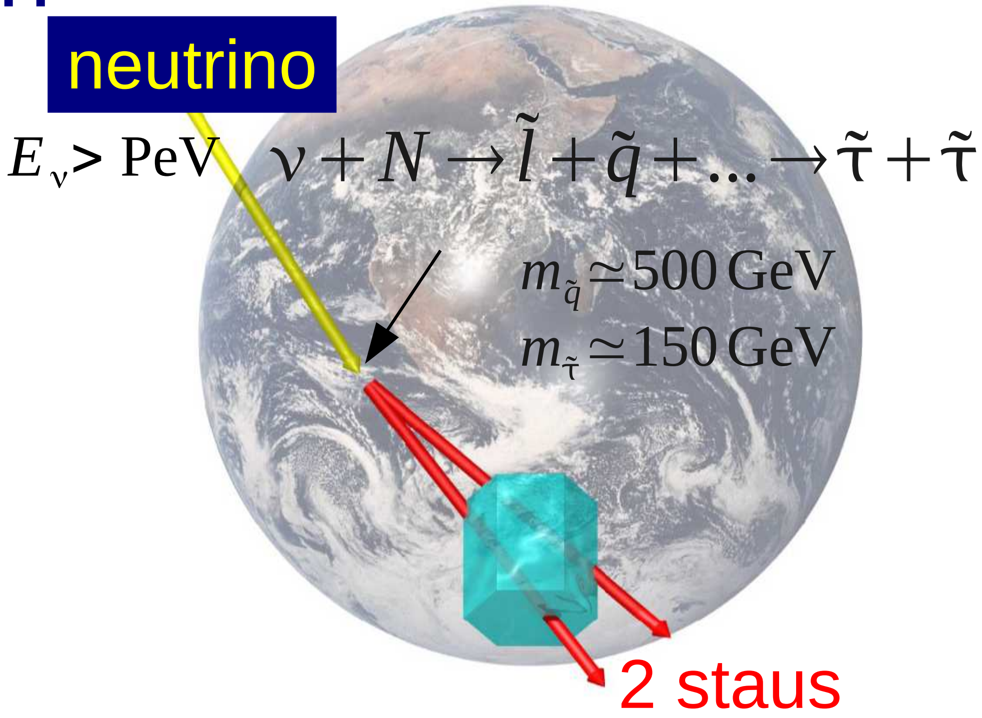
Principle:
- irradiation of the ice with β-rays
- luminescence is emitted isotropically
- measure light coming back and scattered single photons



UHE Neutrino beam on fixed target: Direct (!) SUSY detection

- X-section for heavies: σ ~ $1/M^2$
- Large detector & range compensate
- Direct detection of charged, quasi-stable exotics produced by UHE ***ν***
- **LSP gravitino** (esp. gauge mediated) → NLSP: stau
- Determination of **Lifetimes**

arXiv:1510.05226



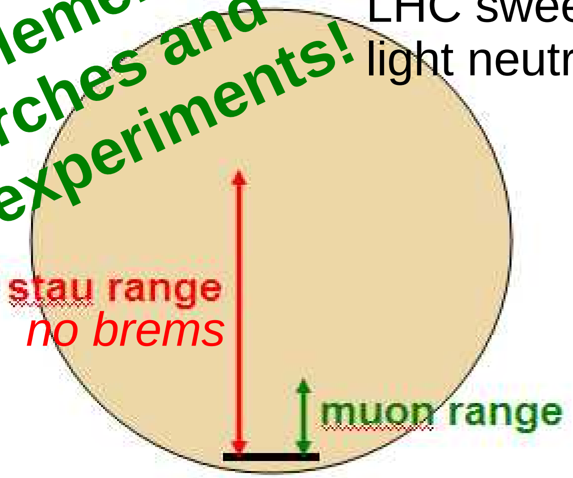
$E_\nu >$ PeV $\quad \nu + N \to \tilde{l} + \tilde{q} + \ldots \to \tilde{\tau} + \tilde{\tau}$

$m_{\tilde{q}} \simeq 500\,\mathrm{GeV}$

$m_{\tilde{\tau}} \simeq 150\,\mathrm{GeV}$

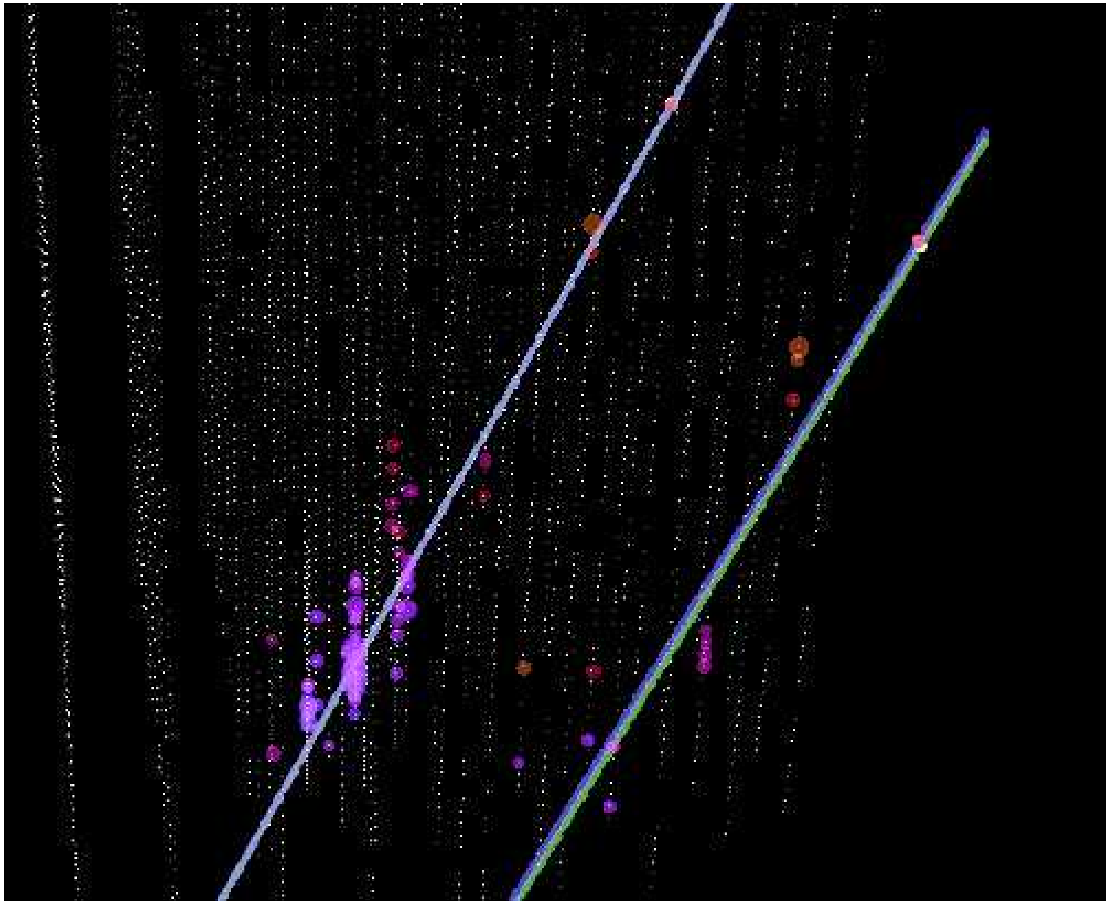
Signal: pair of parallel charged tracks.

Largely complementary to LHC searches and dark matter experiments!

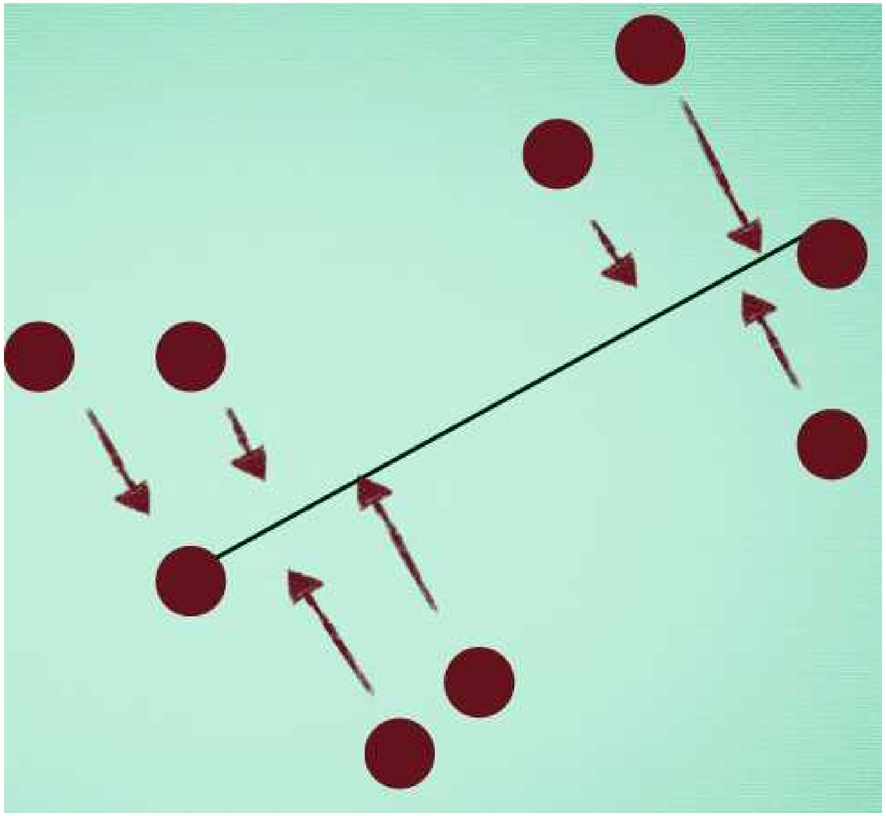


LHC sweet spot: light neutralinos

Parallel tracks … extremely challenging



No dedicated trigger (so far)
Existing one focused on single tracks



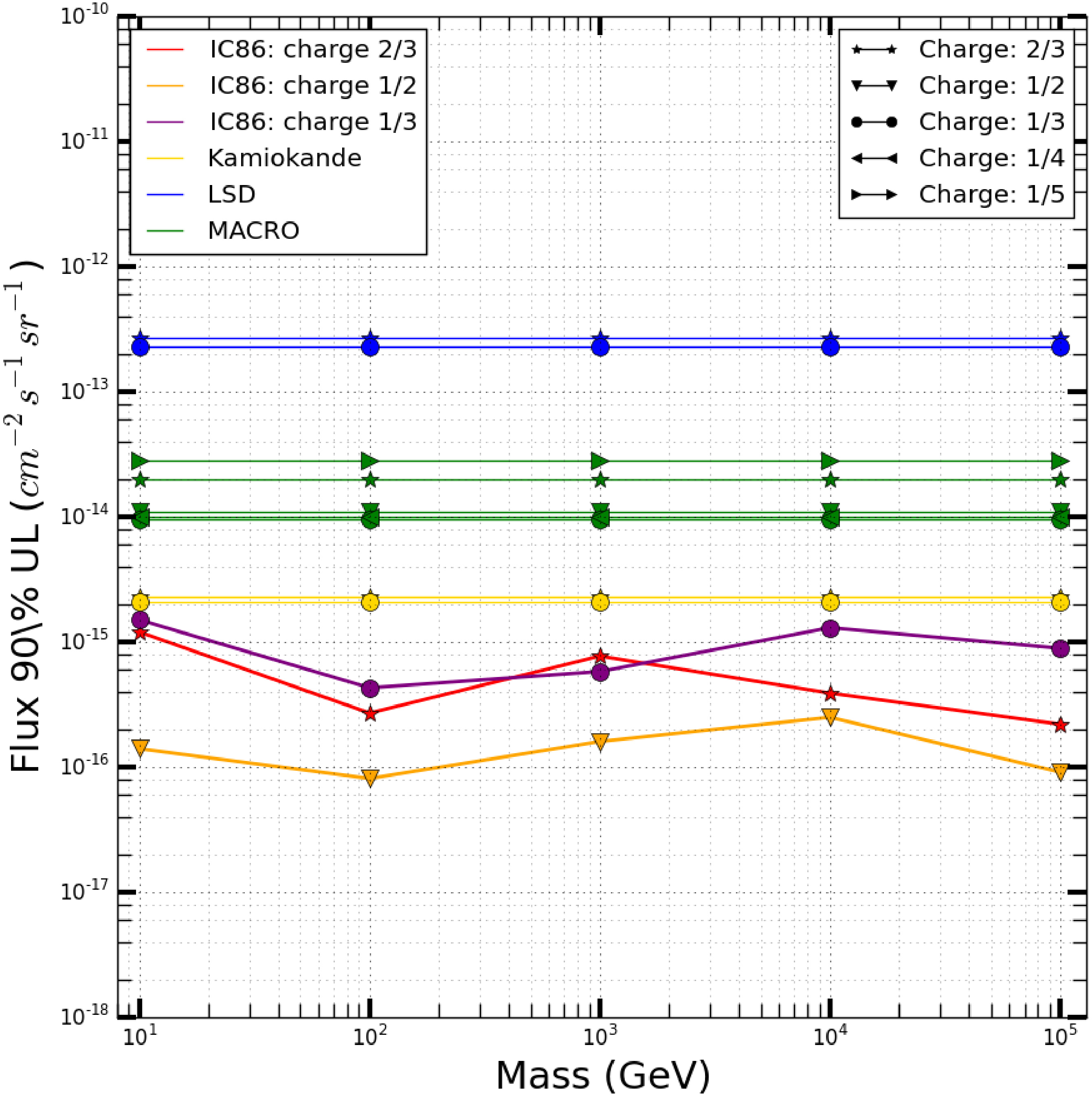
size of "gaps"
with no pulses

Problem: probability of
reconstructing both tracks

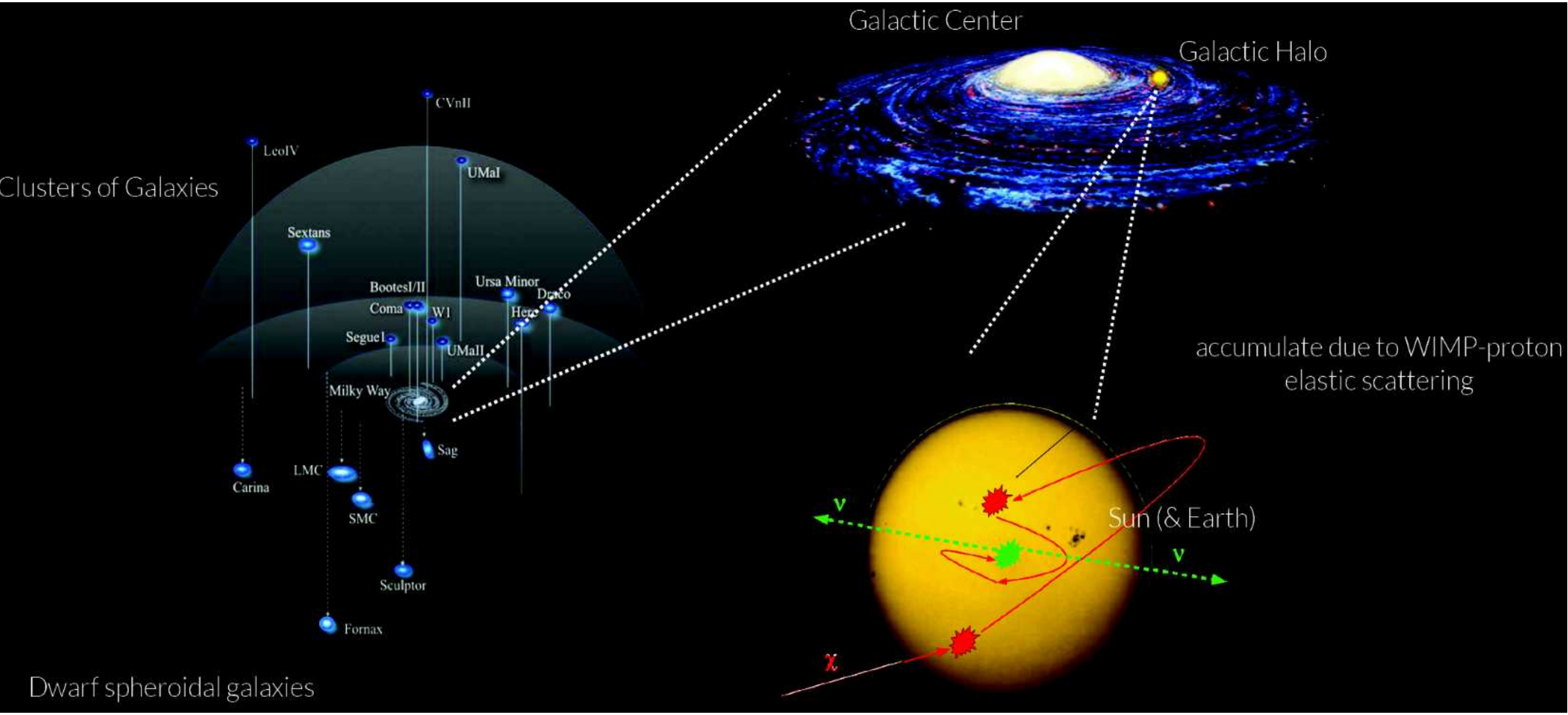
How to (re-)gain sensitivity?

- Dedicated trigger for 2 parallel tracks
- Look for single long dim tracks:
  - dE/dx lower than SM particles: **fractional charges**
  - Track length longer than for SM particles
- Widen scope to Heavy Neutral Leptons (HNLs) e.g. right-handed partners of SM neutrinos:
  - baryon asymmetry
  - neutrino masses and oscillations
  - Dark Matter candidate
  - ν-Telescopes complementary to SHiP proposal:
    - Longer lifetimes
    - Heavier masses

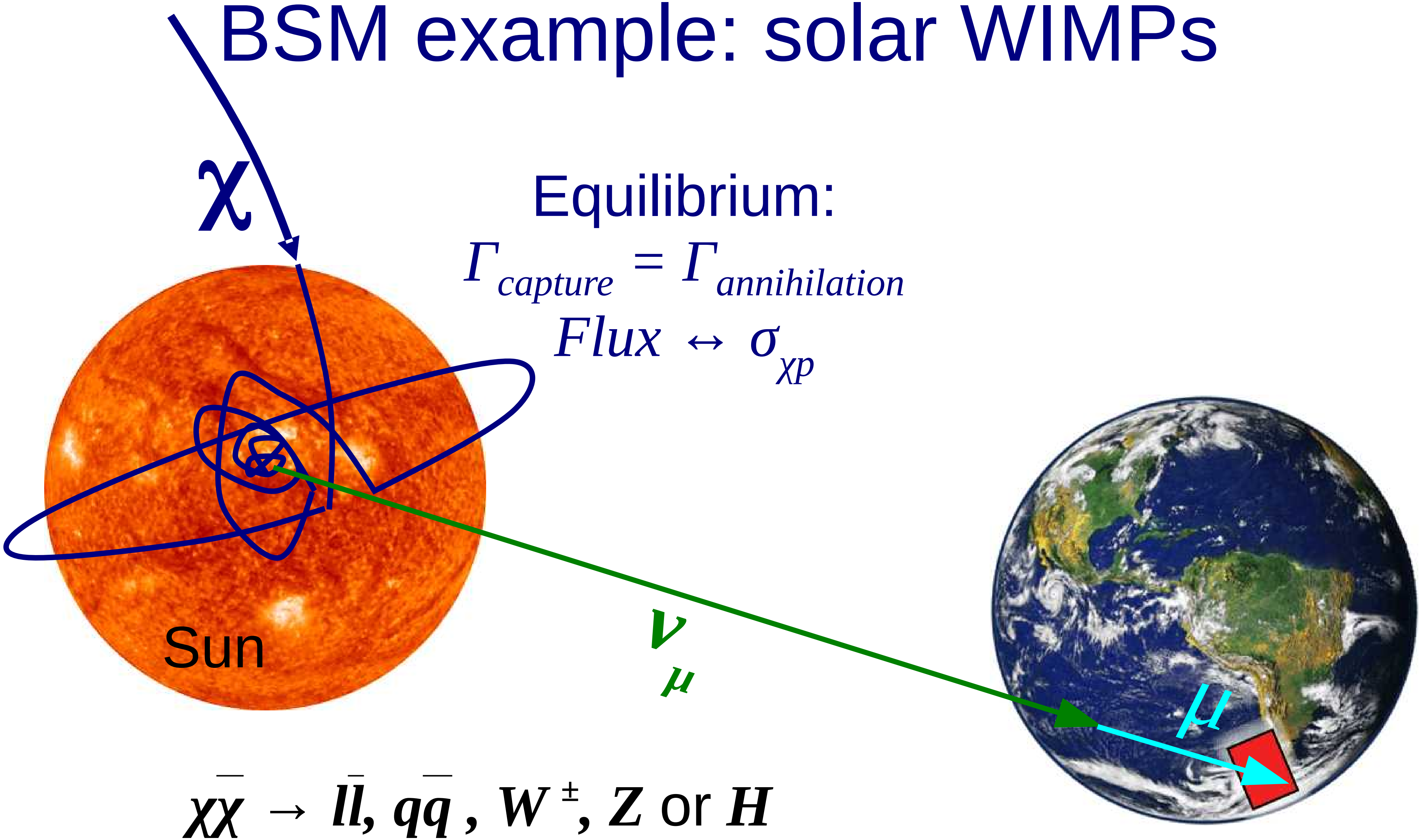
IC-Sensitivity for Fractional Charges



Indirect Dark Matter searches: Accumulation objects



BSM example: solar WIMPs



Equilibrium:

$$\Gamma_{capture} = \Gamma_{annihilation}$$

$$Flux \leftrightarrow \sigma_{\chi p}$$

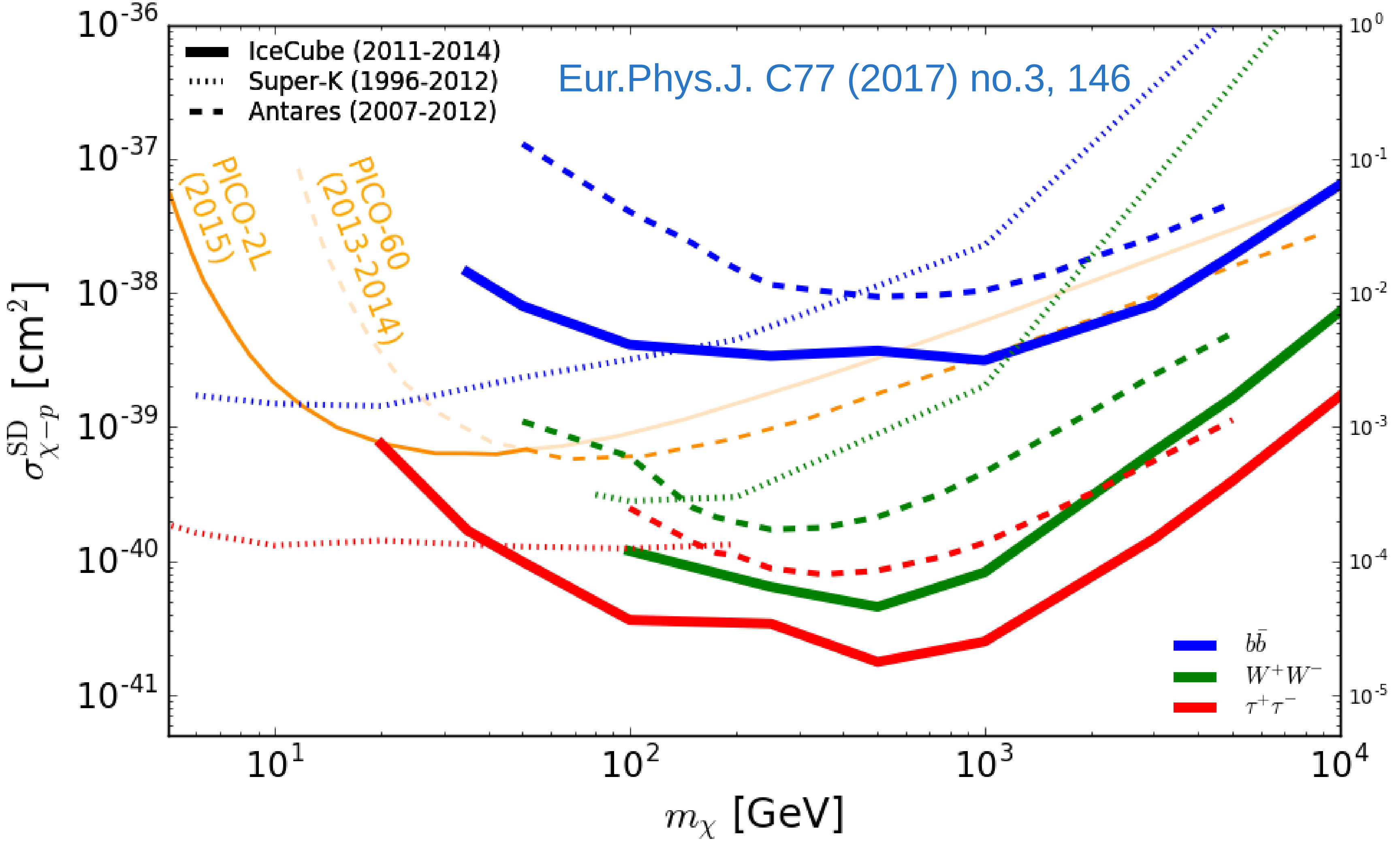
$$\chi\bar{\chi} \rightarrow l\bar{l},\, q\bar{q}\,,\, W^{\pm},\, Z \text{ or } H$$

$$\rightarrow \cdots \rightarrow \nu_\mu$$

Spin dependent χ-p X-section

$$\sigma_{SD} \propto J(J+1)$$

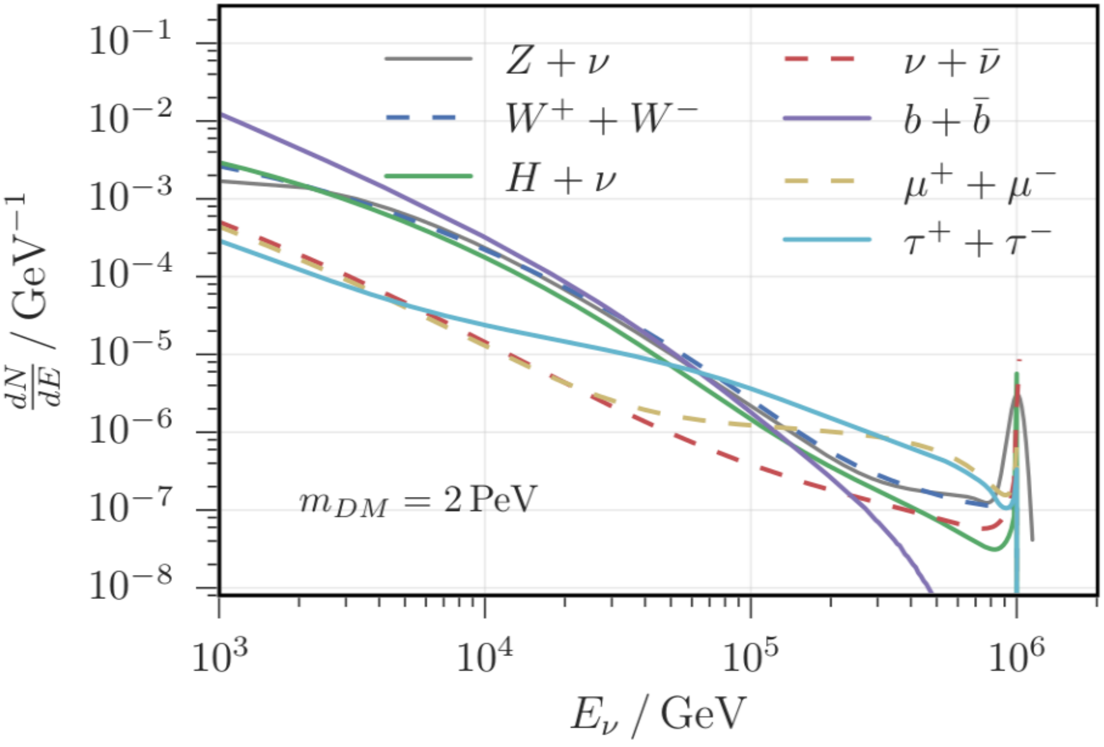
$$\sigma_{SI} \propto A^2$$

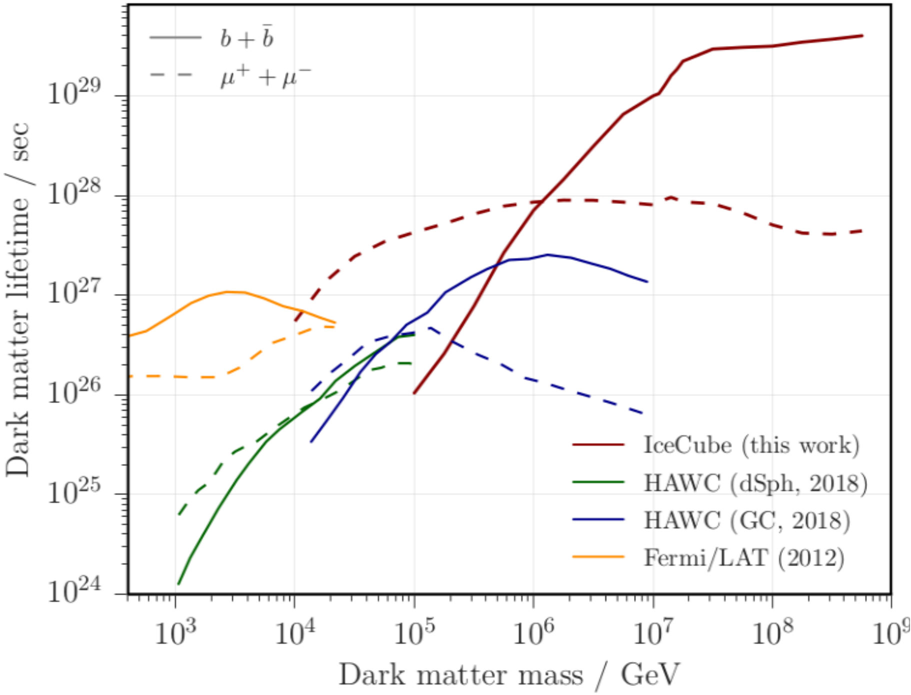


Forthcoming: Searches combining Antares and IceCube

TeV-PeV Dark Matter Decay

Spectral features
in diffuse neutrino flux
for 2 PeV DM mass





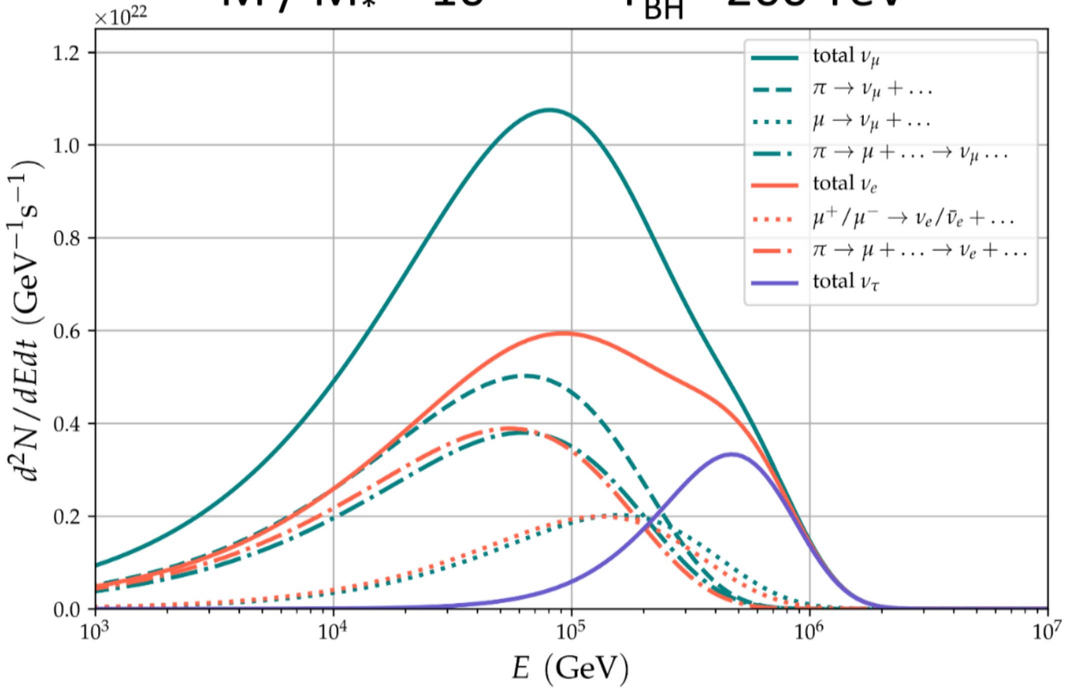
Eur.Phys.J. C78 (2018) no.10, 831

Lower limits …
for once

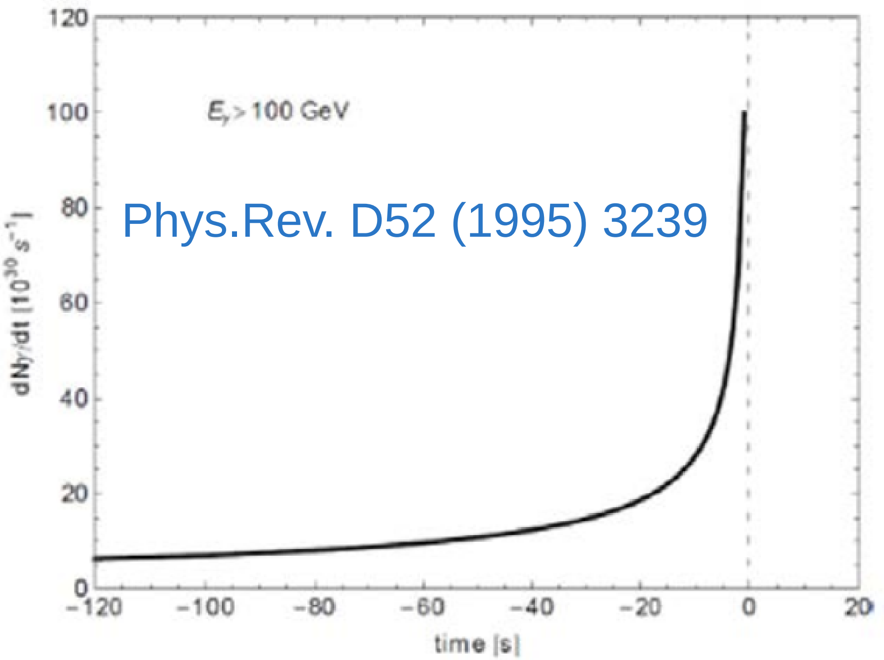
Evaporating primordial black holes as flaring point sources

Today might be the ideal cosmological epoch

$M / M_* = 10^{-7}$ $T_{BH} \approx 200$ TeV



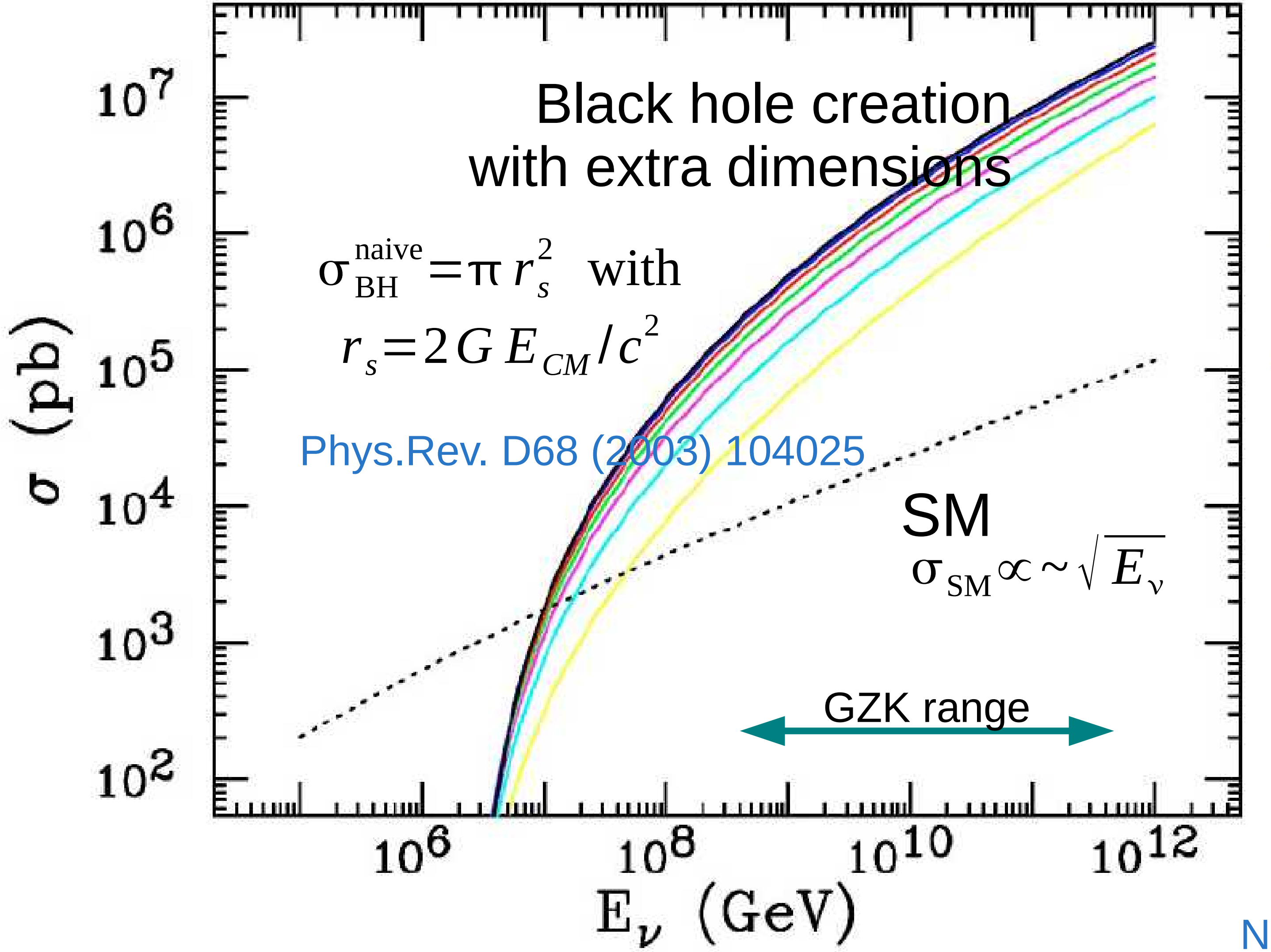
Phys.Rev. D41 (1990) 3052



Phys.Rev. D52 (1995) 3239

Signature:
Hawking radiation of neutrinos
→ chirp with increasing energy

Neutrino cross section and black hole creation



Black hole creation
with extra dimensions

$\sigma_{\mathrm{BH}}^{\mathrm{naive}} = \pi r_s^2$ with

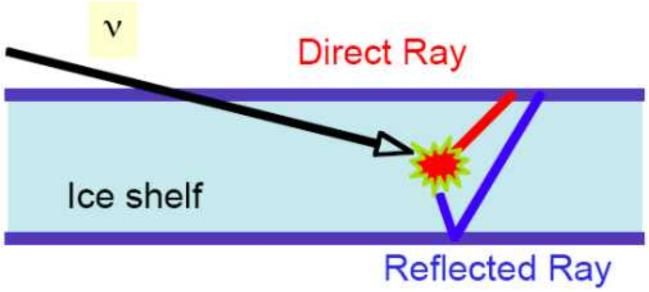
$r_s = 2 G E_{CM} / c^2$

Phys.Rev. D68 (2003) 104025

SM

$\sigma_{\mathrm{SM}} \propto \sim \sqrt{E_\nu}$

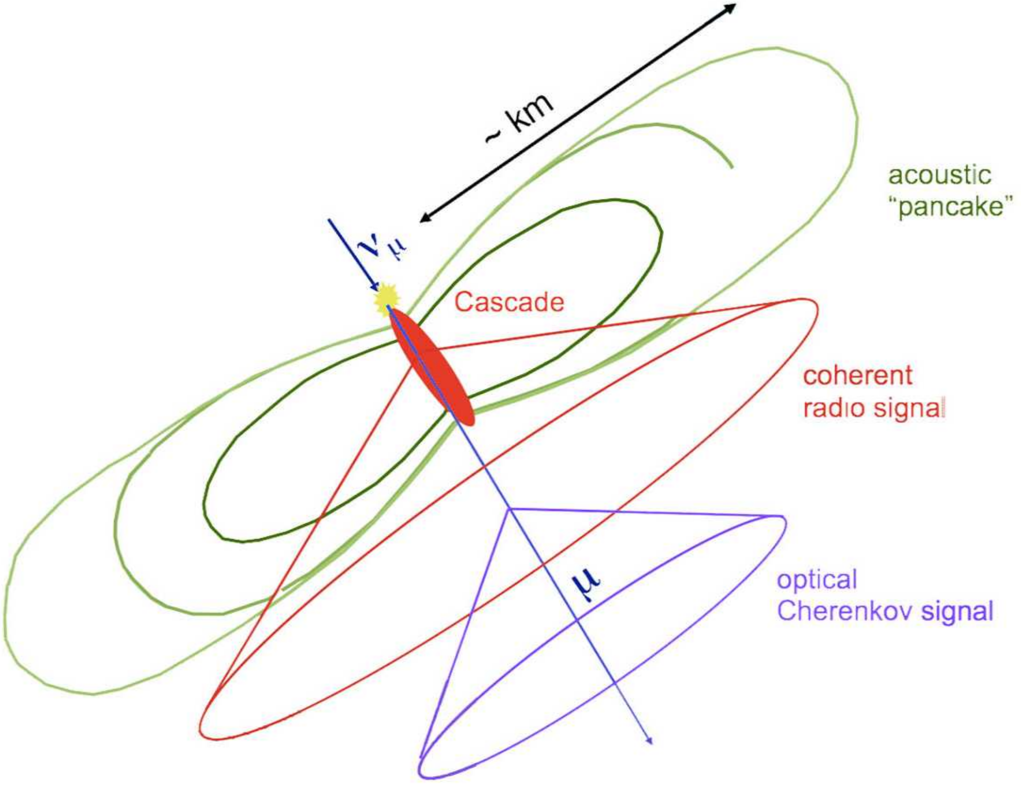
GZK range



Measurement:
depth distribution
& zenith angle

Nature 551 (2017) 596

EHE detection methods in ice

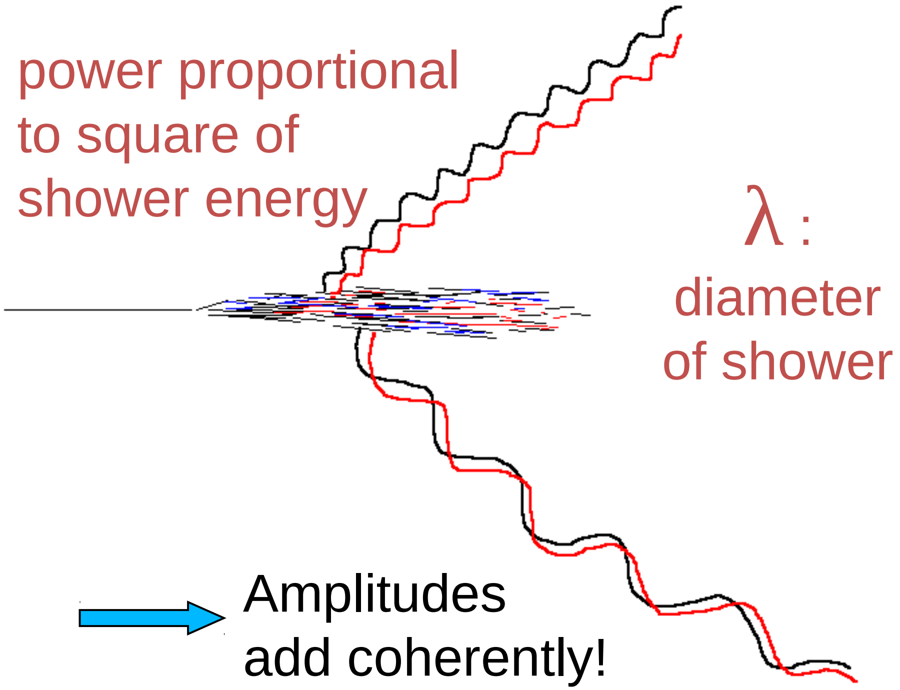


Ongoing R&D for future GZK energy neutrino detectors focus on radio and acoustic detection.

Promise: Cheap sensors & sparse spacing

Propagation of sound and RF are being studied using in situ measurements.

Optimal technologies and array configurations under investigation.

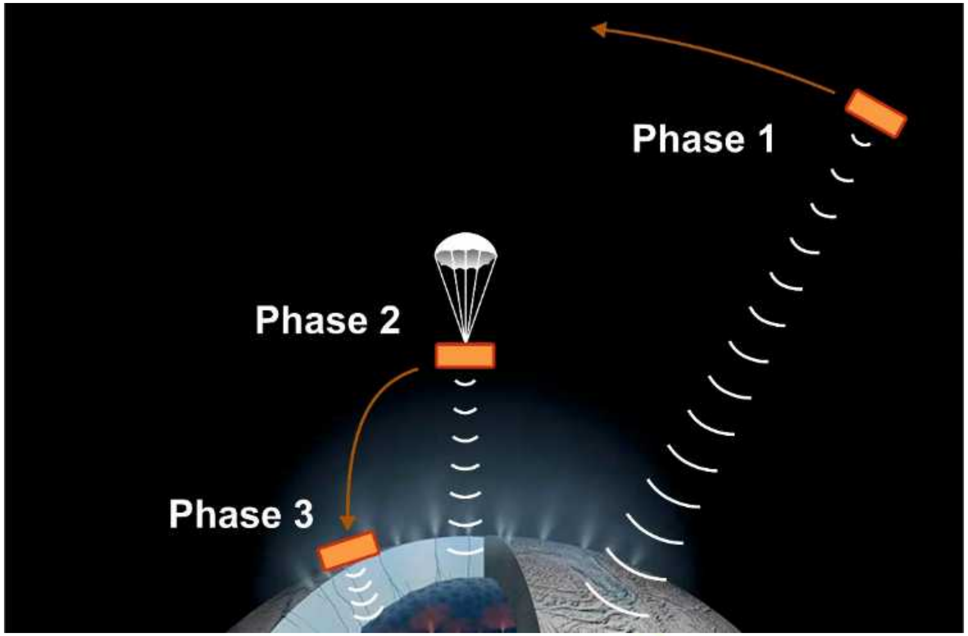


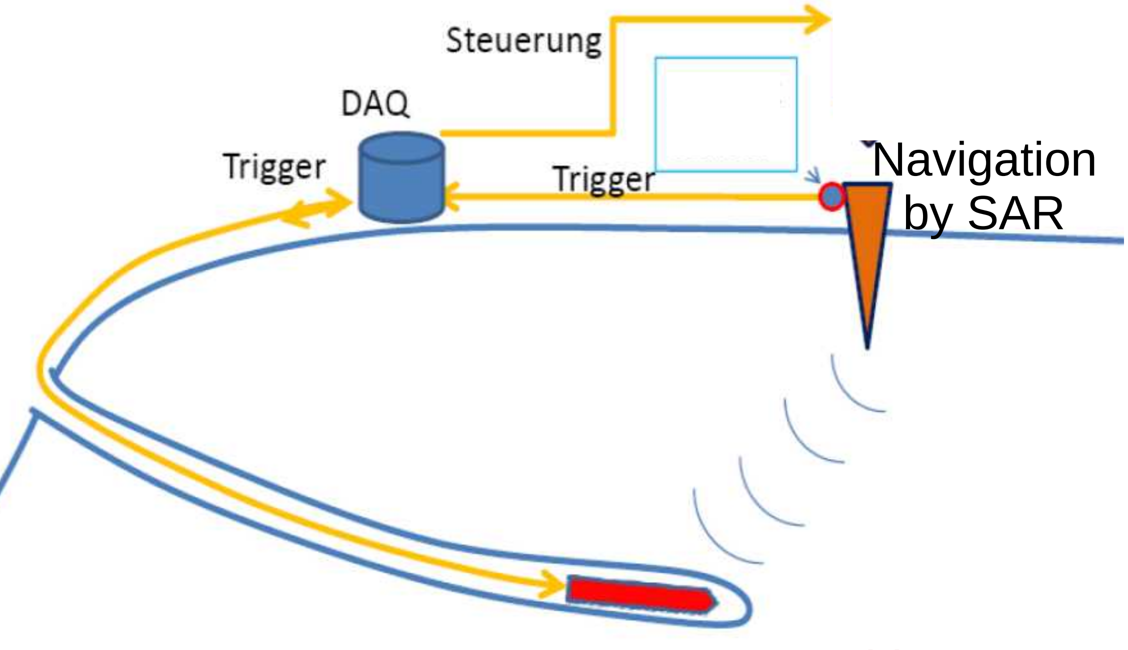
power proportional to square of shower energy

λ : diameter of shower

Amplitudes add coherently!

Spin-Off: Astro-Biology Enceladus-Explorer



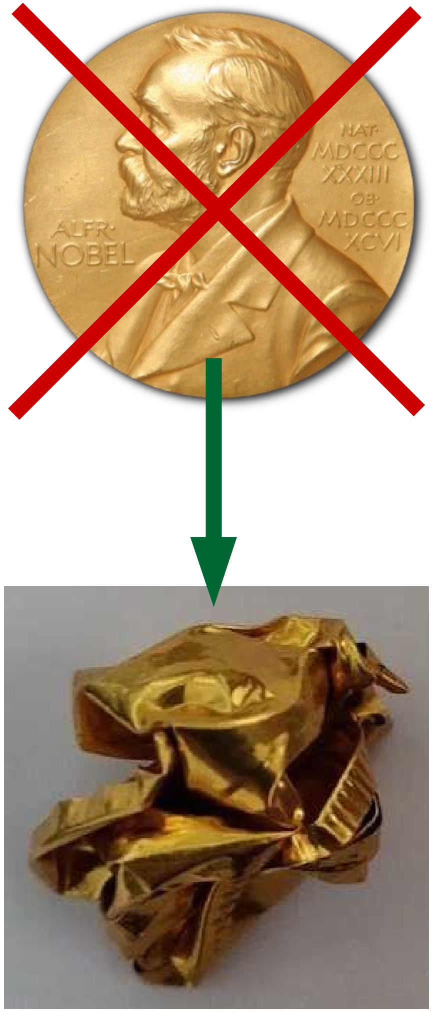


Navigation by SAR

EnEx

autonomous drill

Summary & Outlook



We are stretching neutrino telescopes far beyond design goals and primary objectives …

… if you have a model that involves neutrinos or weak couplings, we can probably probe it.

Major research infrastructures